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(12) **United States Patent**
Hagstrom et al.

(10) **Patent No.: US 11,067,187 B2**
(45) **Date of Patent: Jul. 20, 2021**

(54) **FLUIDIC CONTROL VALVE WITH SMALL DISPLACEMENT ACTUATORS**

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(72) Inventors: **Nathan Paul Hagstrom**, Minneapolis, MN (US); **Thomas Richard Chase**, Minneapolis, MN (US)

(73) Assignee: **Regents of the University of Minnesota**, Minneapolis, MN (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 238 days.

(21) Appl. No.: **16/444,563**

(22) Filed: **Jun. 18, 2019**

(65) **Prior Publication Data**

US 2019/0301628 A1 Oct. 3, 2019

Related U.S. Application Data

(63) Continuation-in-part of application No. 15/399,150, filed on Jan. 5, 2017, now Pat. No. 10,330,212.

(Continued)

(51) **Int. Cl.**
F16K 31/00 (2006.01)
F16K 1/42 (2006.01)

(52) **U.S. Cl.**
CPC ***F16K 31/007*** (2013.01); ***F16K 1/42*** (2013.01); *Y10T 137/8242* (2015.04); *Y10T 137/86759* (2015.04); *Y10T 137/87265* (2015.04)

(58) **Field of Classification Search**
CPC F16K 31/007; F16K 47/08; Y10T 137/87265; Y10T 137/86759; Y10T 137/8242; Y10T 137/86718

(Continued)

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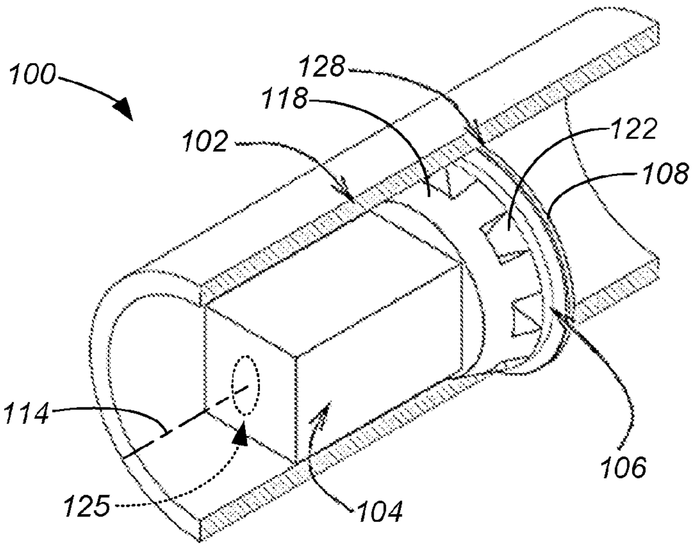
(57) **ABSTRACT**

A fluidic control valve configured to control a flow of fluid through a conduit includes a piezostack actuator, a seal plate having a sealing face, an orifice plate including a plurality of orifices, and a suspension connected to the seal plate. The piezostack actuator is configured to displace the seal plate along a longitudinal axis of the conduit between a closed position, in which the sealing face engages the orifice plate, seals the orifices of the orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the orifice plate to open the valve. The suspension is configured to flex and adjust an orientation of the sealing face relative to the orifice plate during movement of the seal plate from the open position to the closed position.

20 Claims, 16 Drawing Sheets



Related U.S. Application Data

(60) Provisional application No. 62/287,655, filed on Jan. 27, 2016.

(58) **Field of Classification Search**
USPC 251/129.06, 129.22; 137/599.01, 625.28, 137/625.33, 554
See application file for complete search history.

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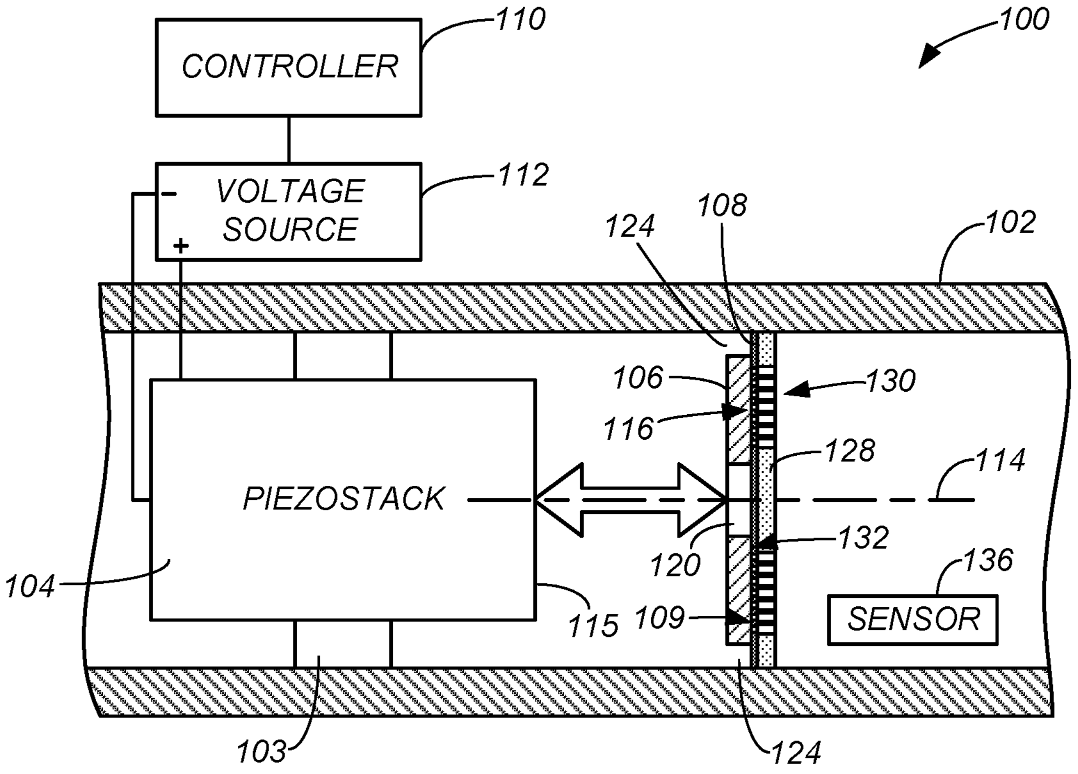
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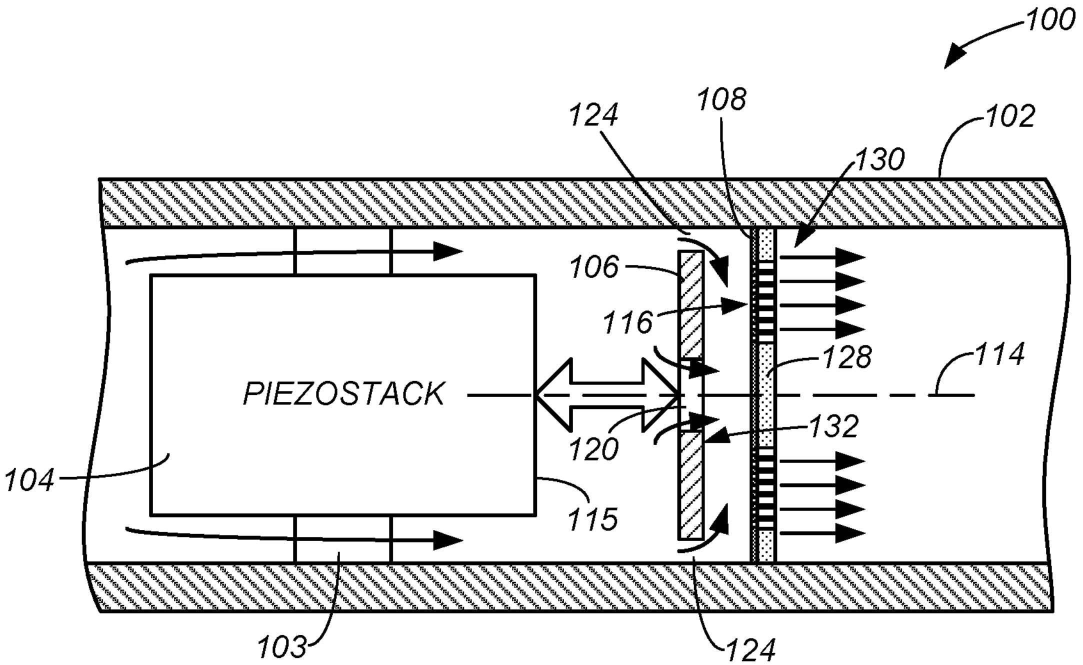
FIG. 1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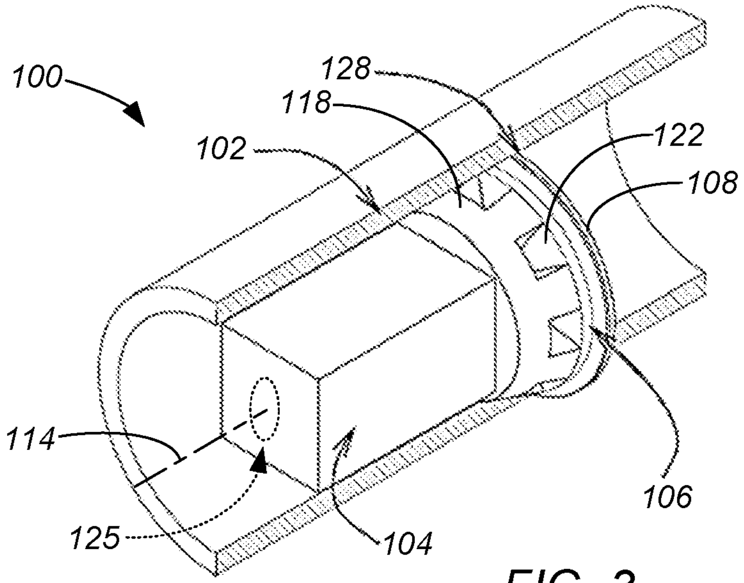
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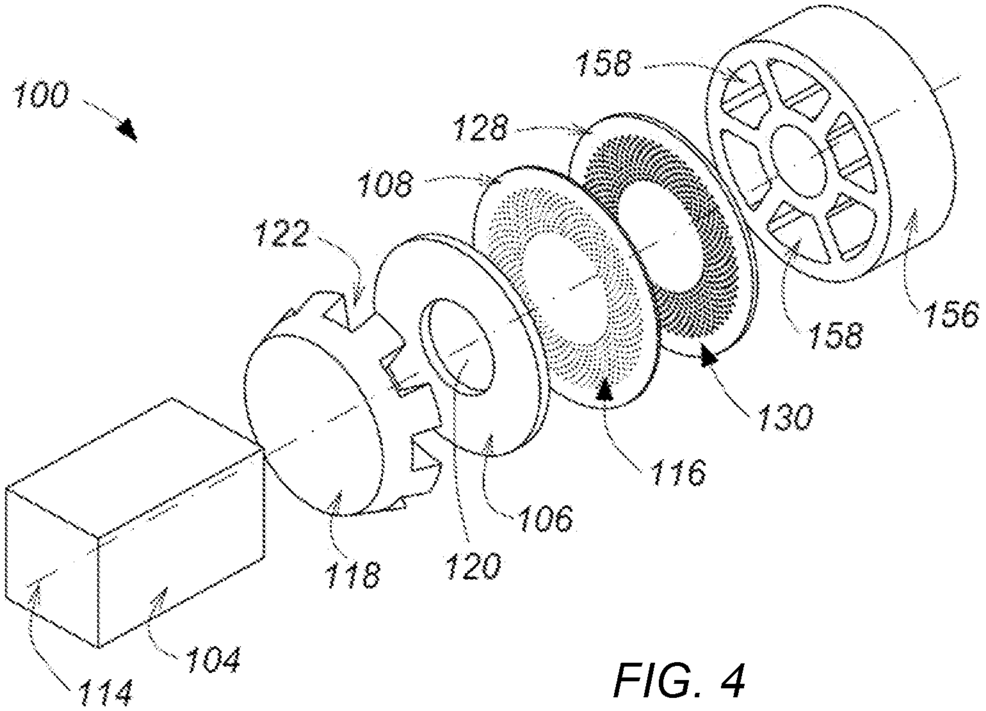
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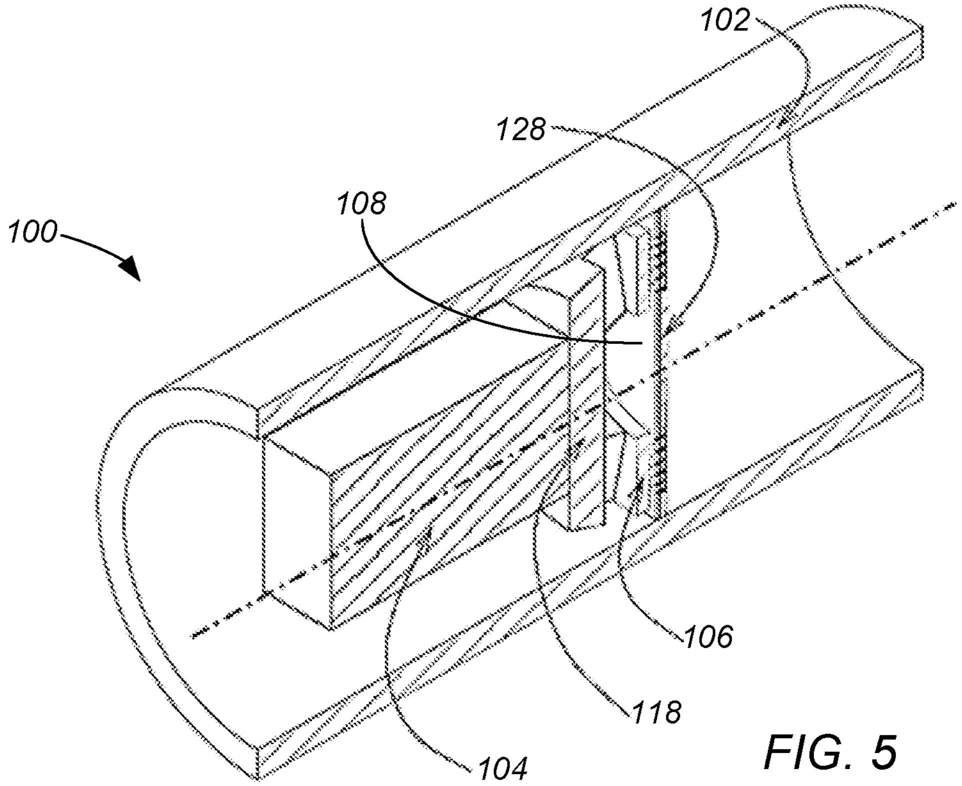

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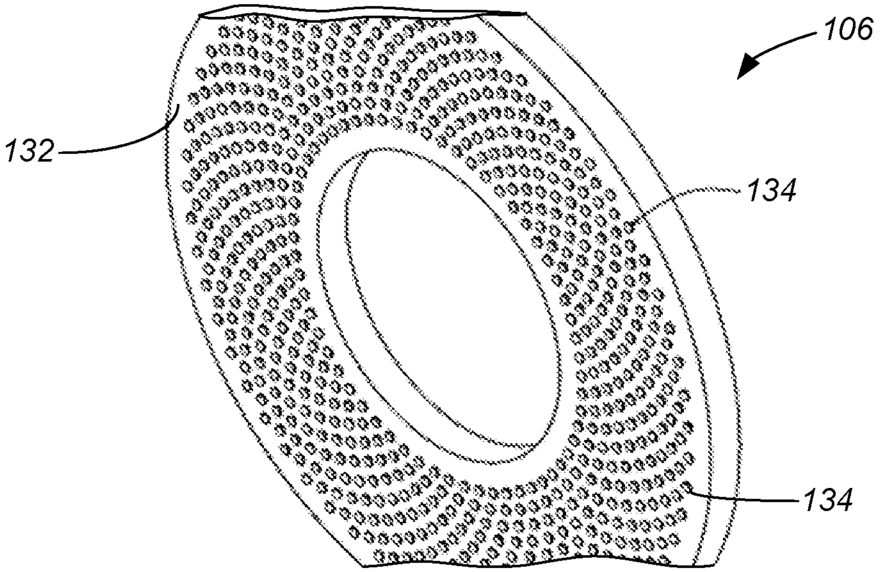

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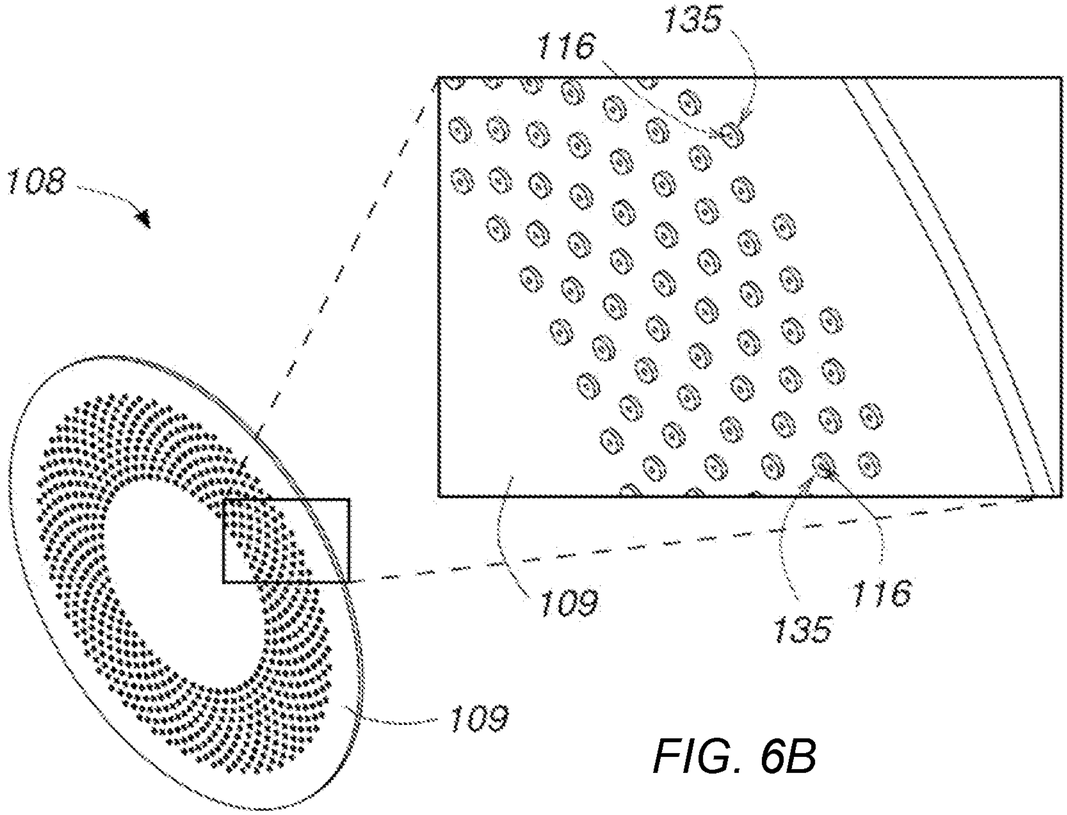

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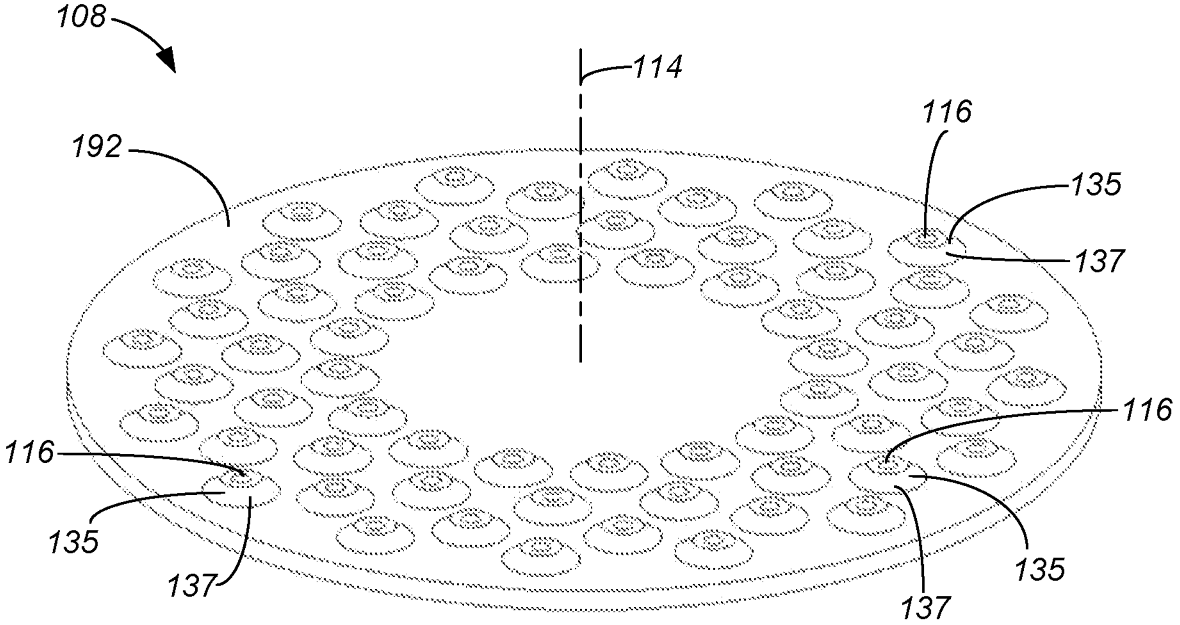
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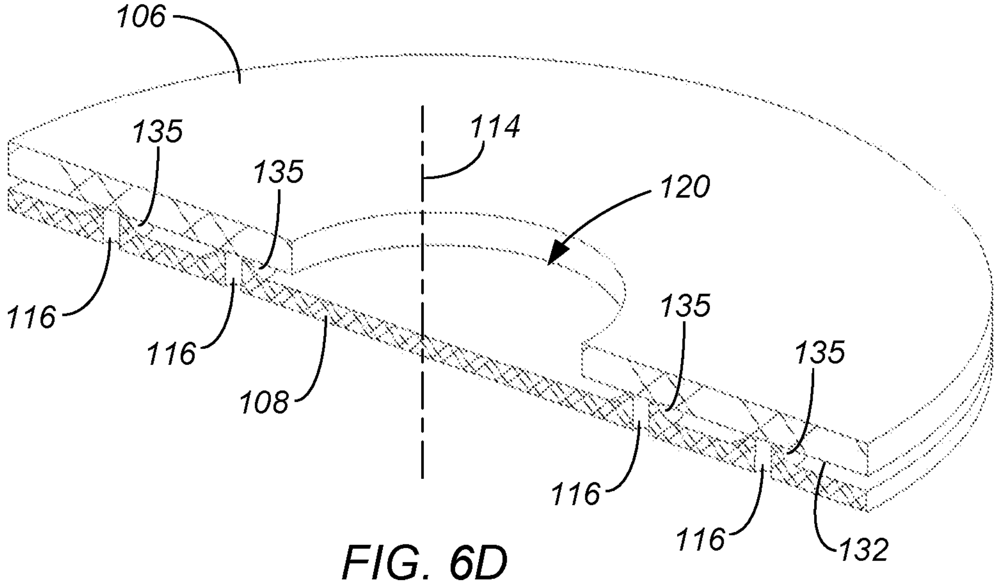
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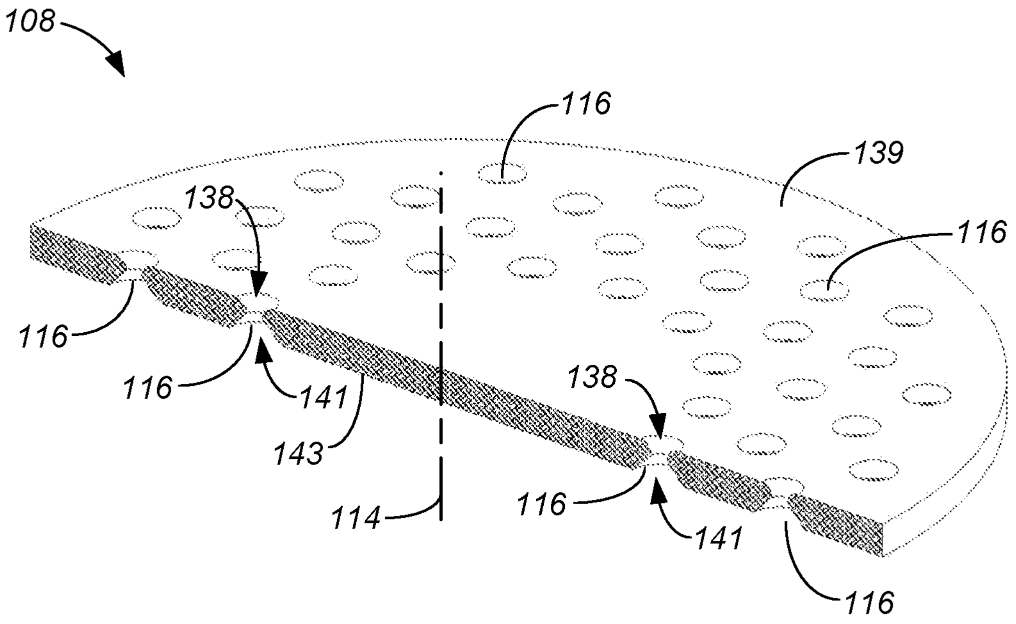
FIG. 6D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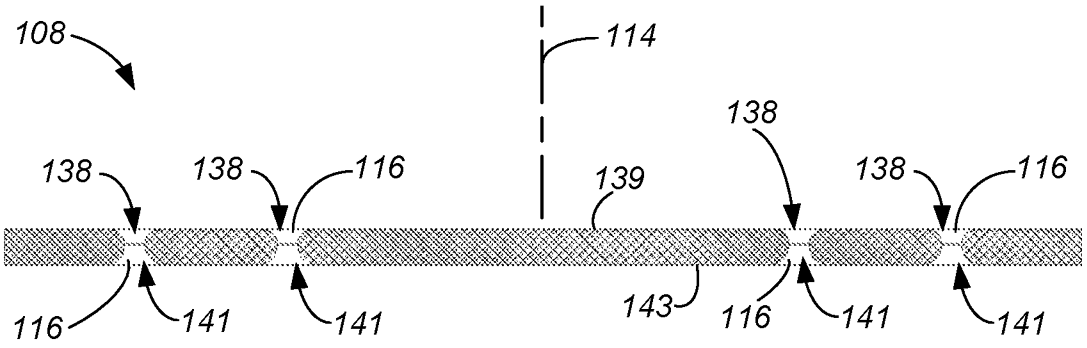
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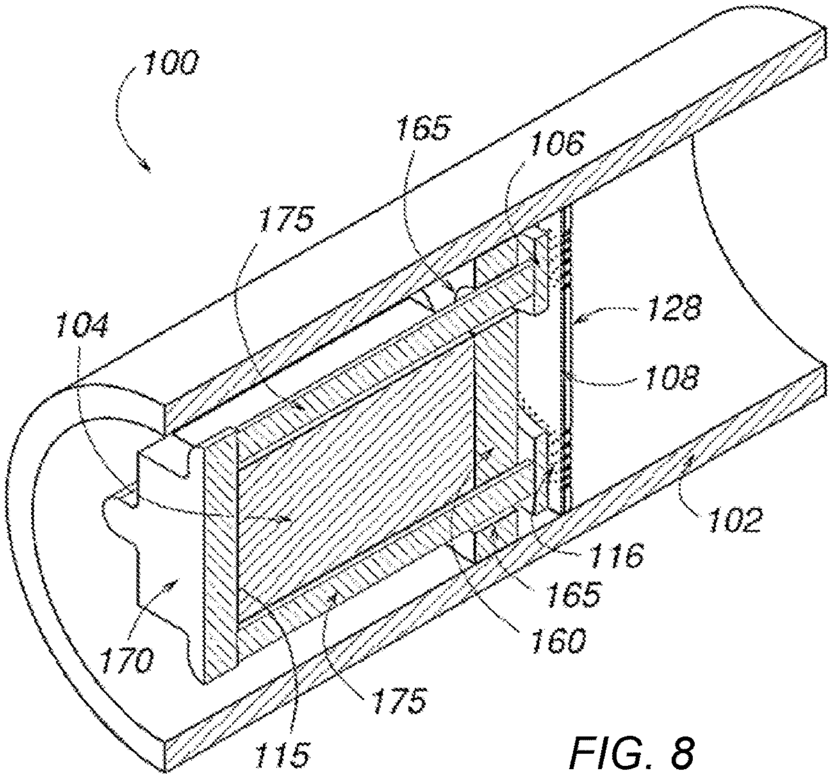
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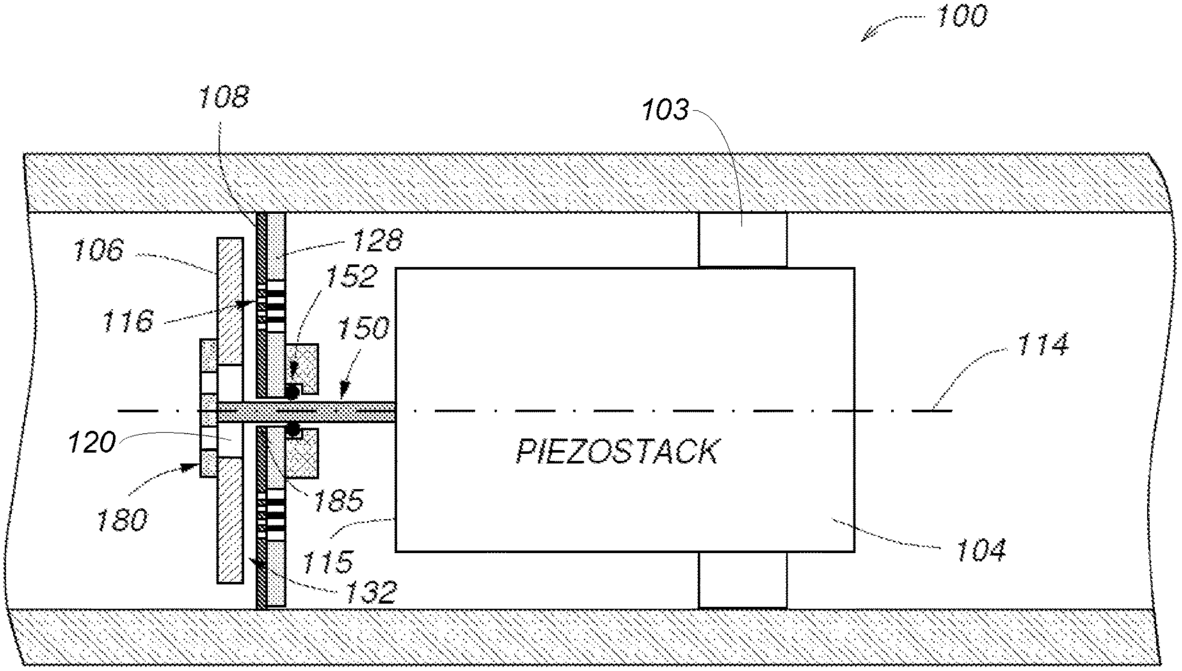
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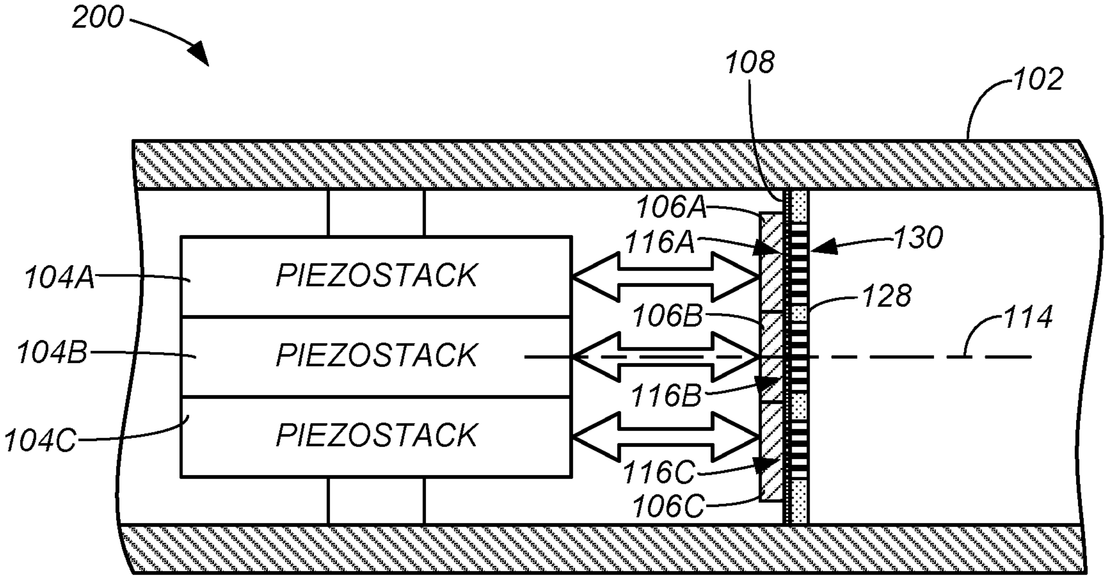
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FIG. 10

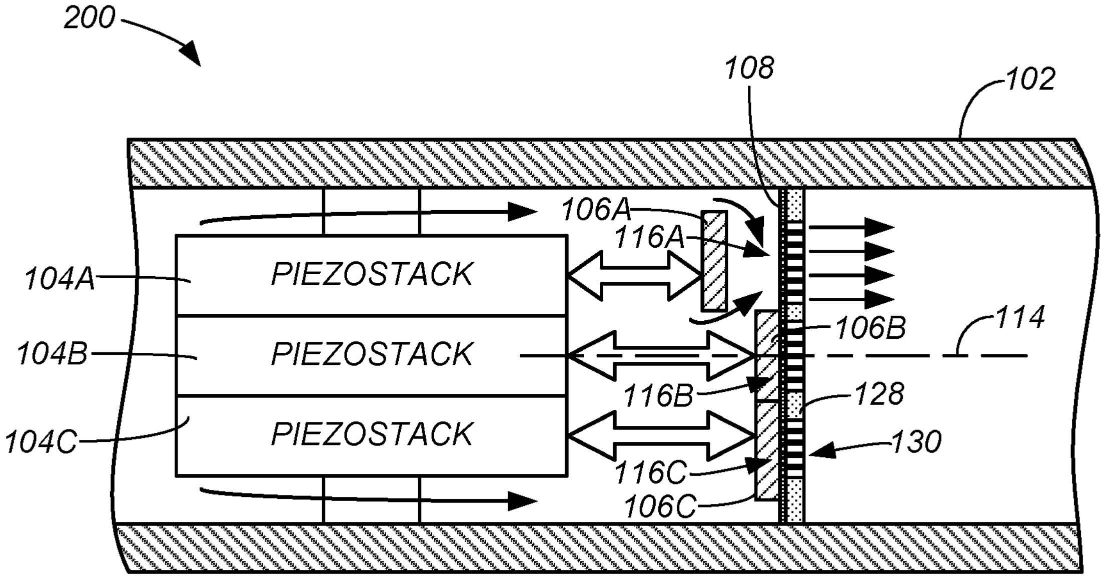
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FIG. 11

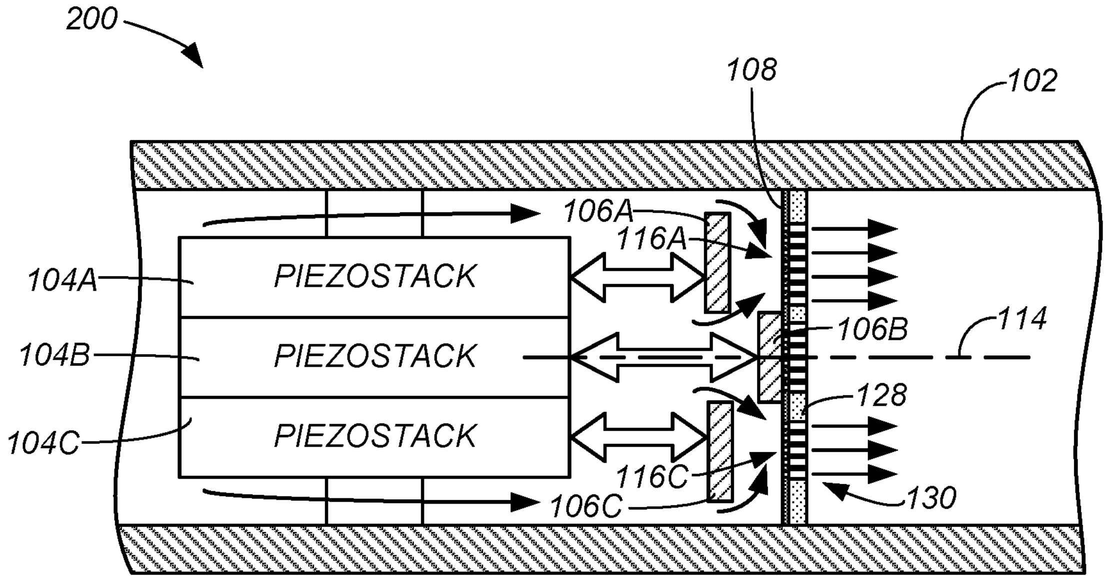
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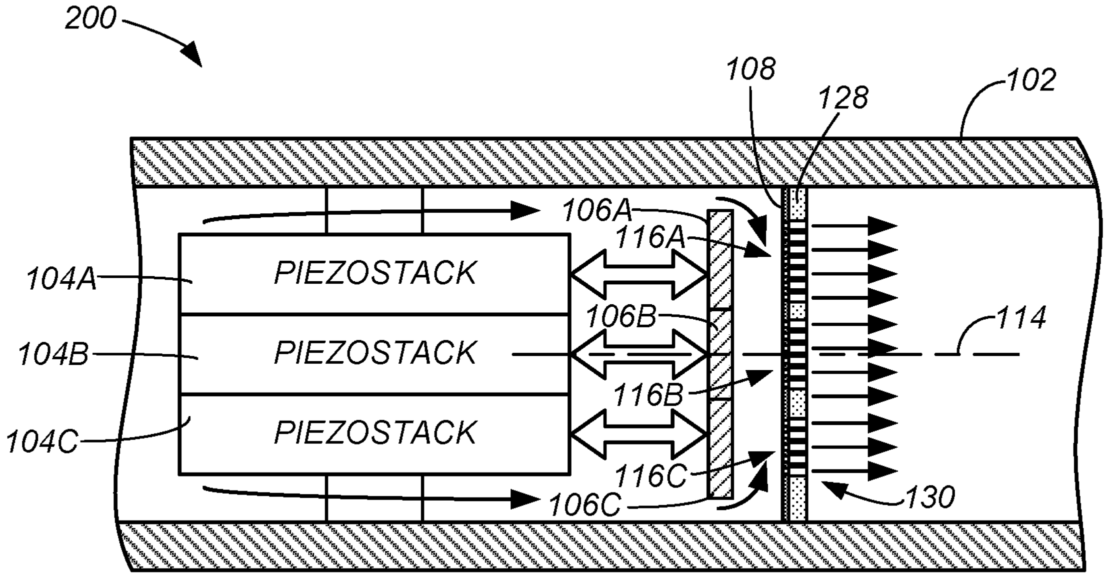
FIG. 12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130

FIG. 13

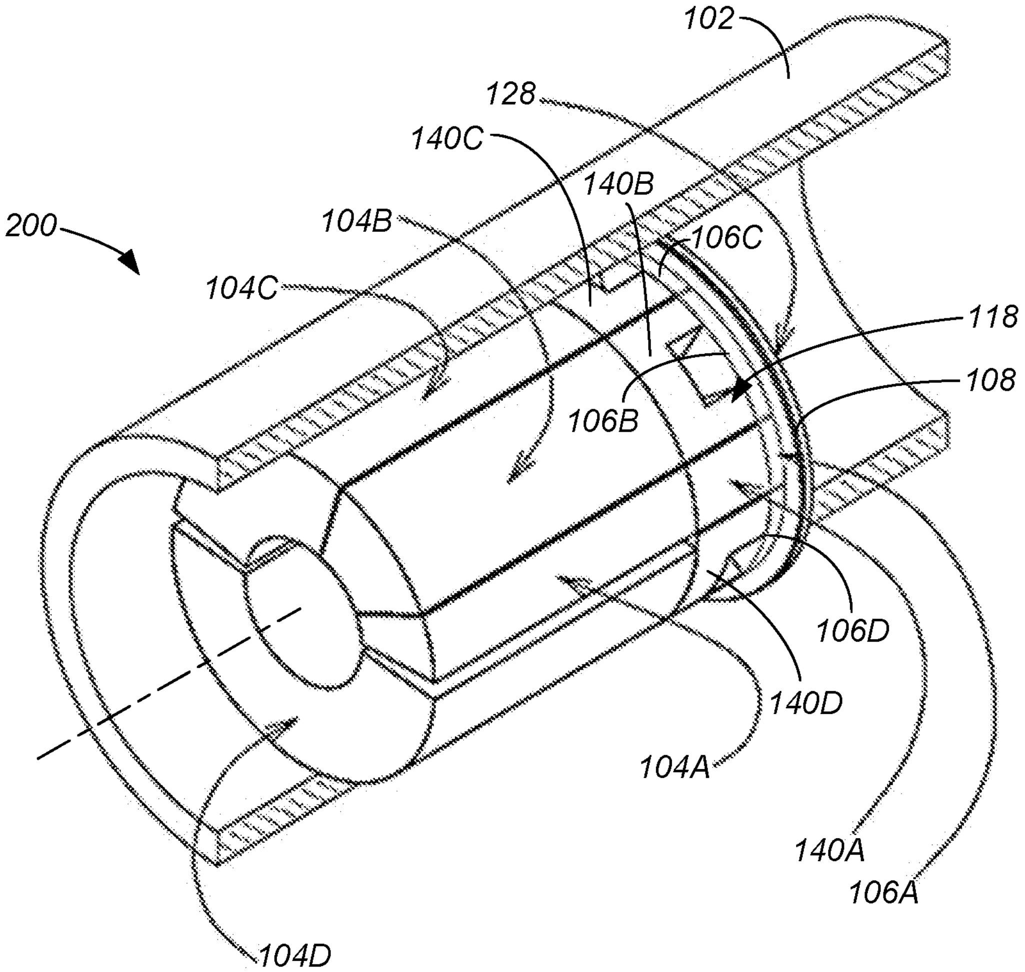

102
128
140C
140B
106C
200
104B
104C
118
108
106B
106D
140D
104A
140A
106A
104D

FIG 14

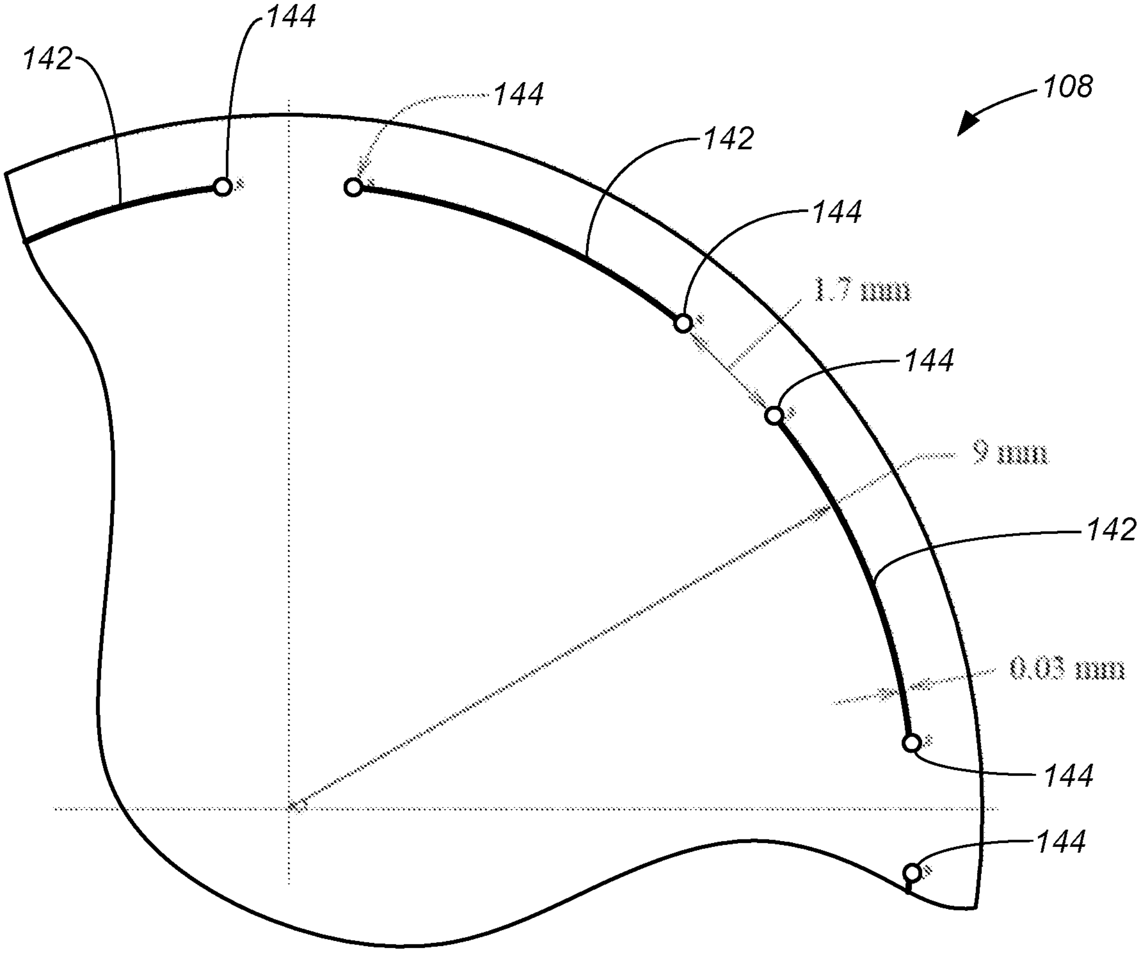


FIG. 15

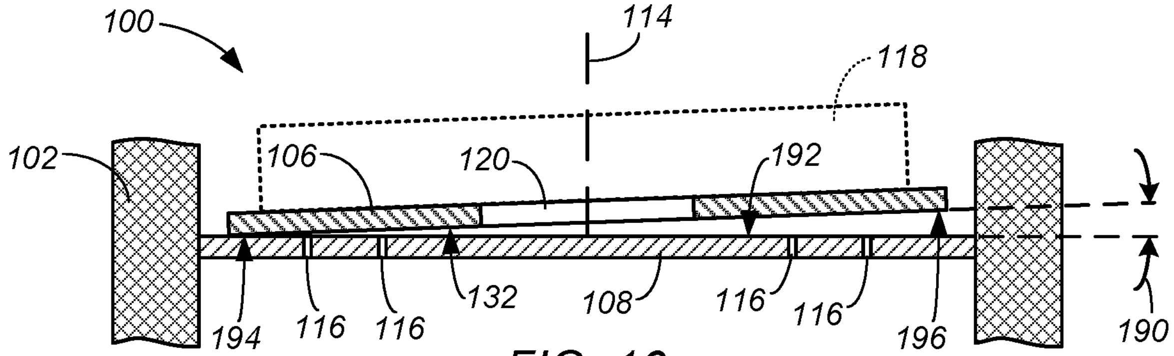


FIG. 16

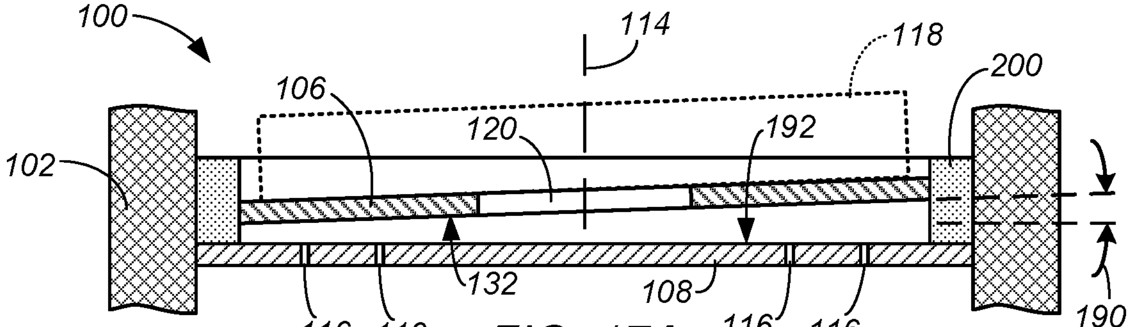


FIG. 17A

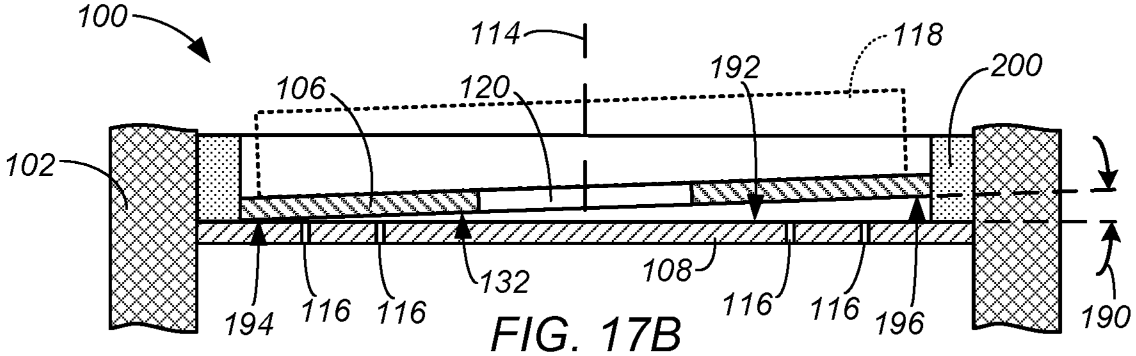


FIG. 17B

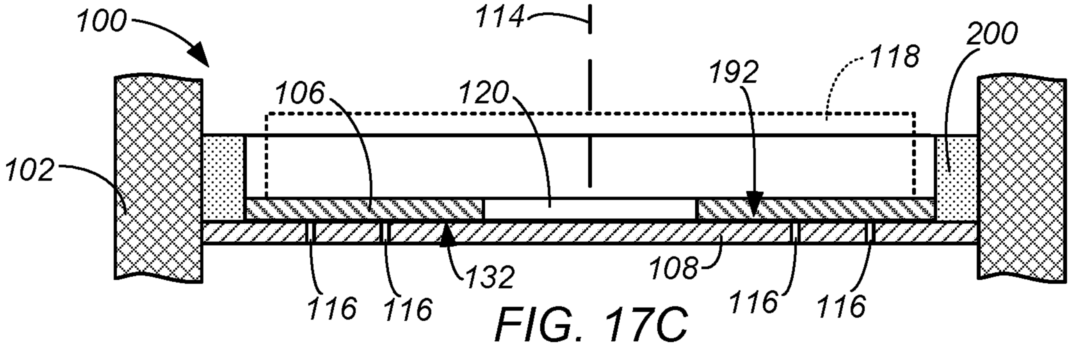


FIG. 17C

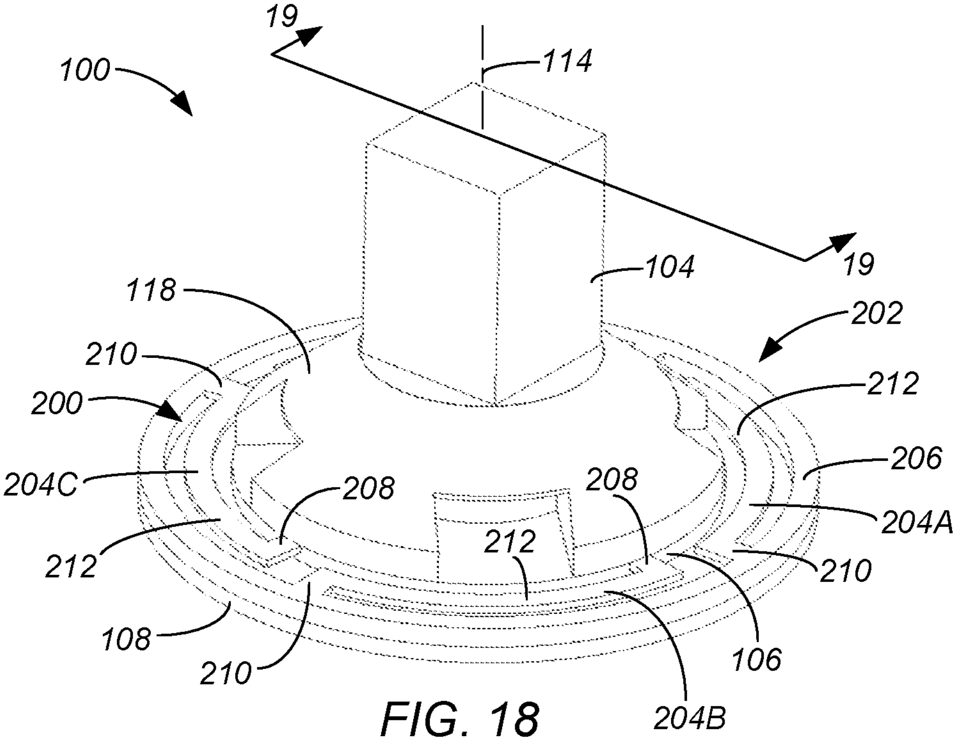

19
114
100
104
19
118
202
210
212
200
206
204C
208
208
204A
212
212
210
108
106
210
204B

FIG. 18

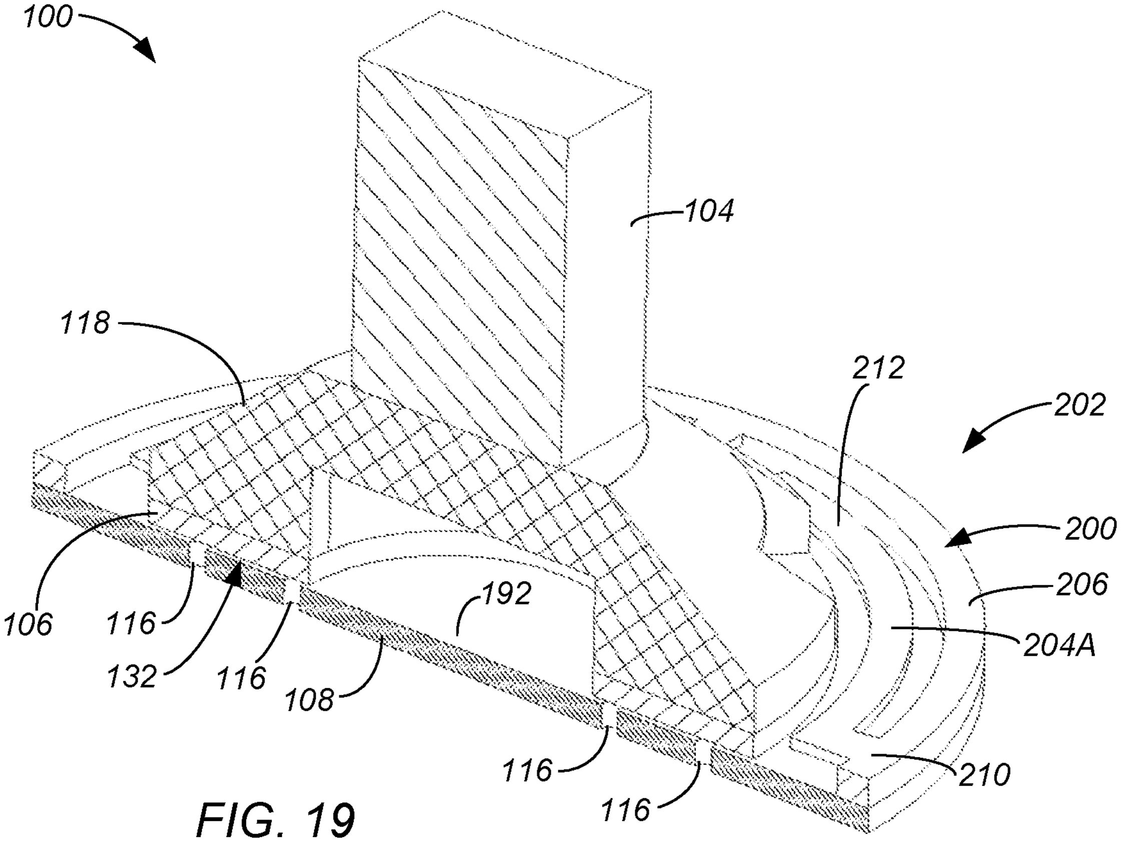

100
104
118
212
202
200
206
106
116
132
116
192
108
204A
116
210
116

FIG. 19

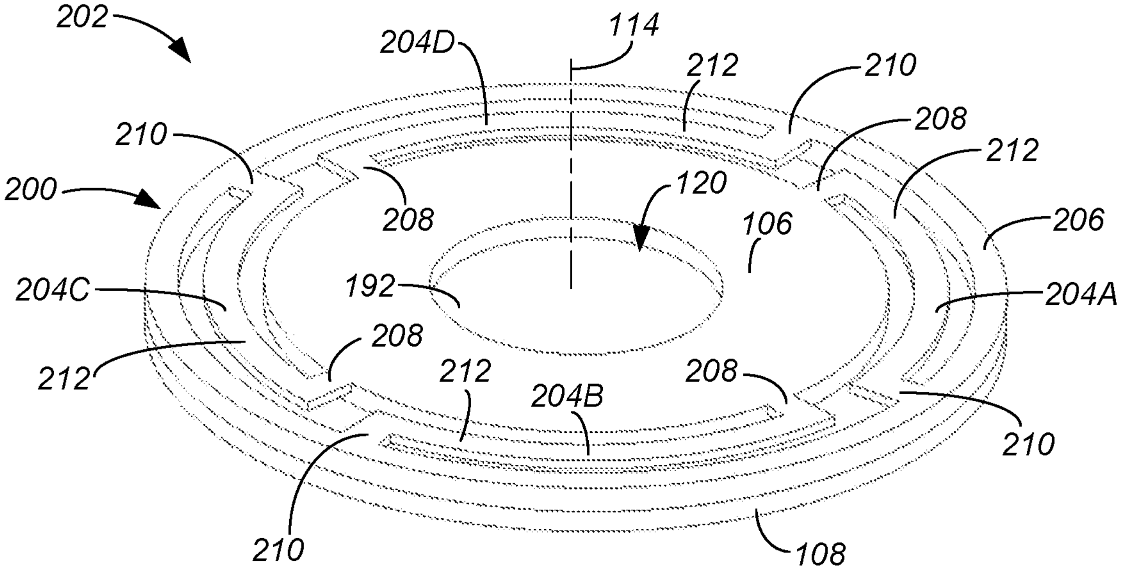
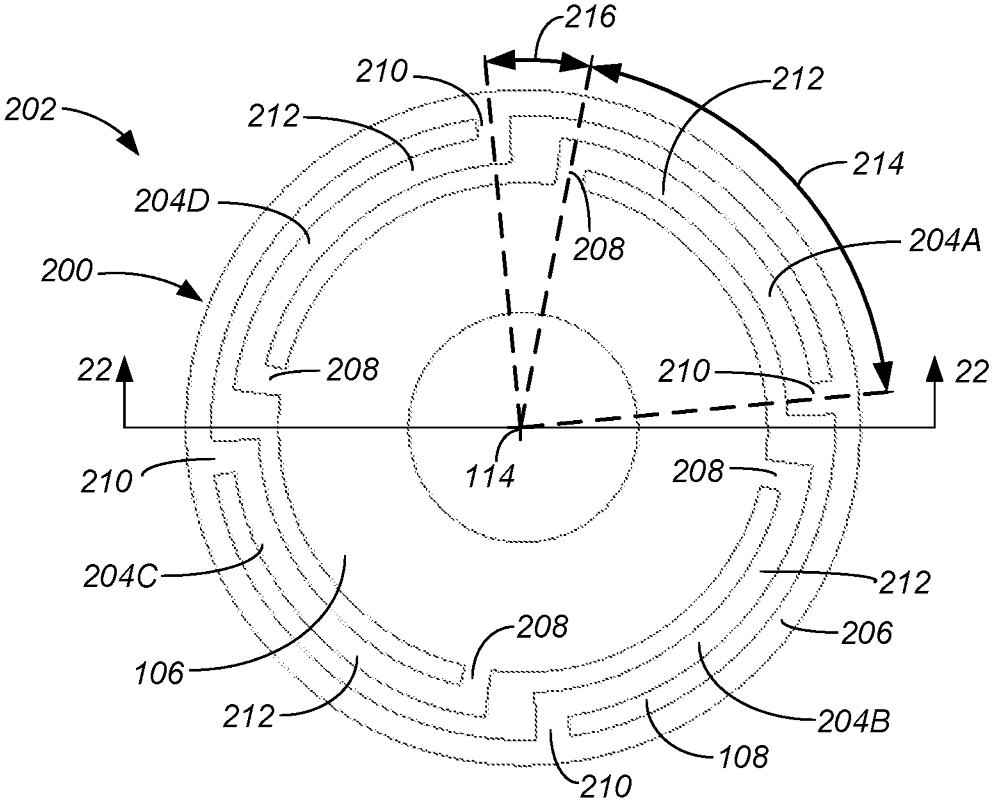

202
204D
114
212
210
210
208
212
200
120
206
208
106
204C
192
204A
208
212
212
204B
208
210
210
108

FIG. 20


216
210
212
202
214
212
204D
208
204A
200
22
208
210
22
114
210
208
204C
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208
206
212
204B
108
210

FIG. 21

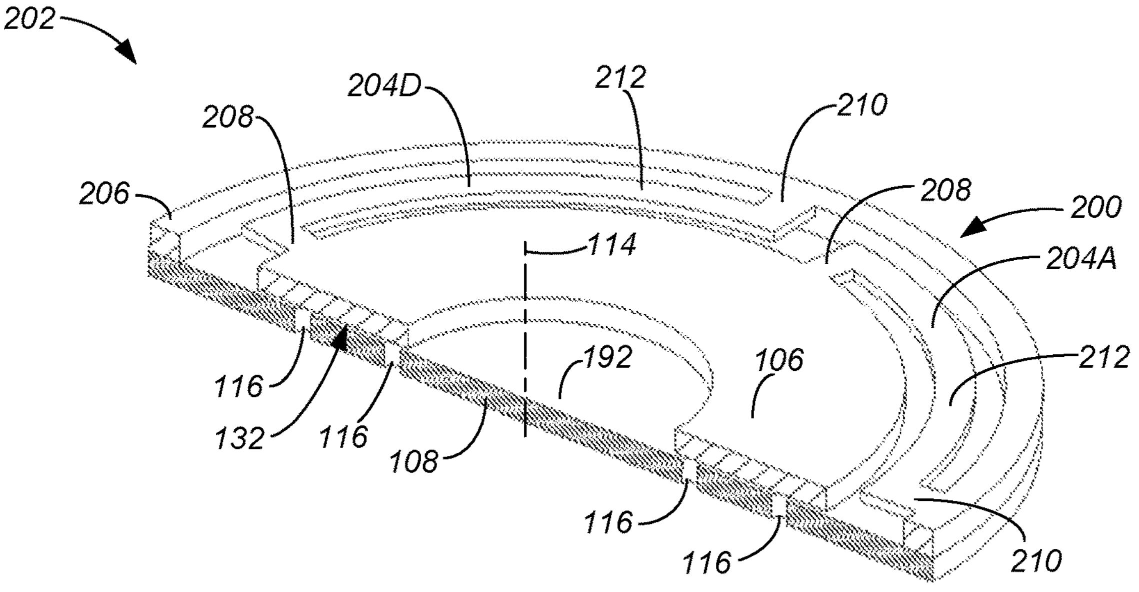
202
204D
212
210
208
206
208
200
114
204A
192
106
212
116
132
116
108
116
116
210

FIG. 22

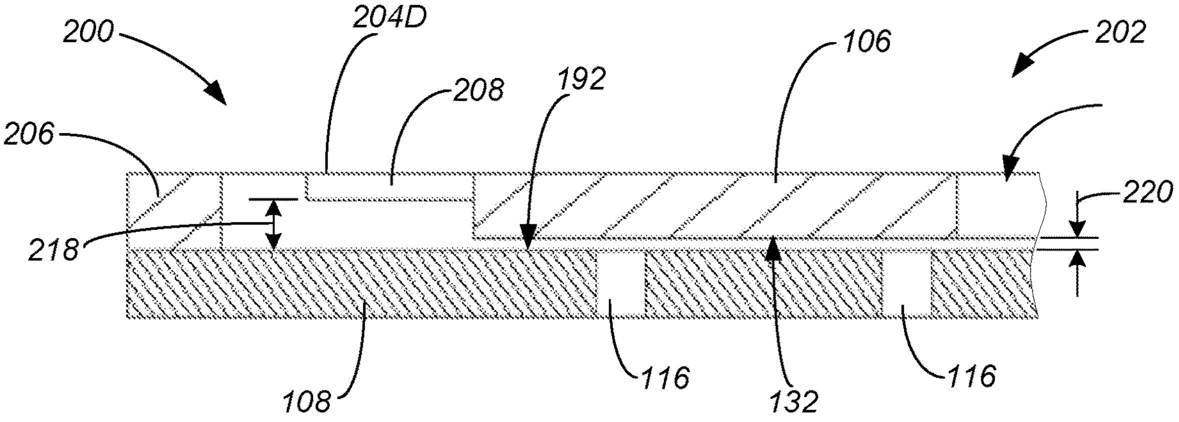
200
204D
106
202
208
192
206
220
218
108
116
132
116

FIG. 23

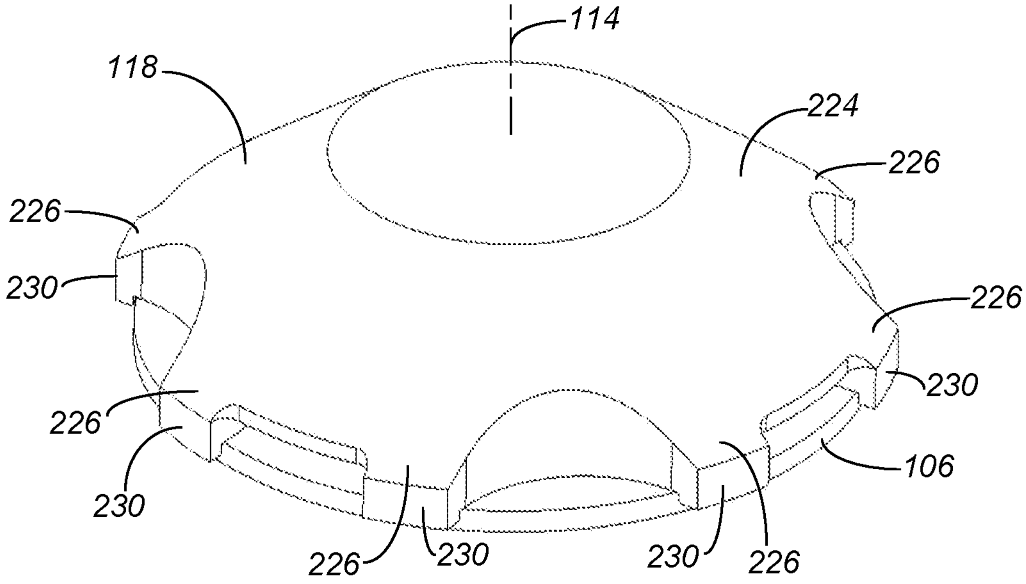
114
118
224
226
226
230
226
230
226
106
230
226
230
230
226

FIG. 24

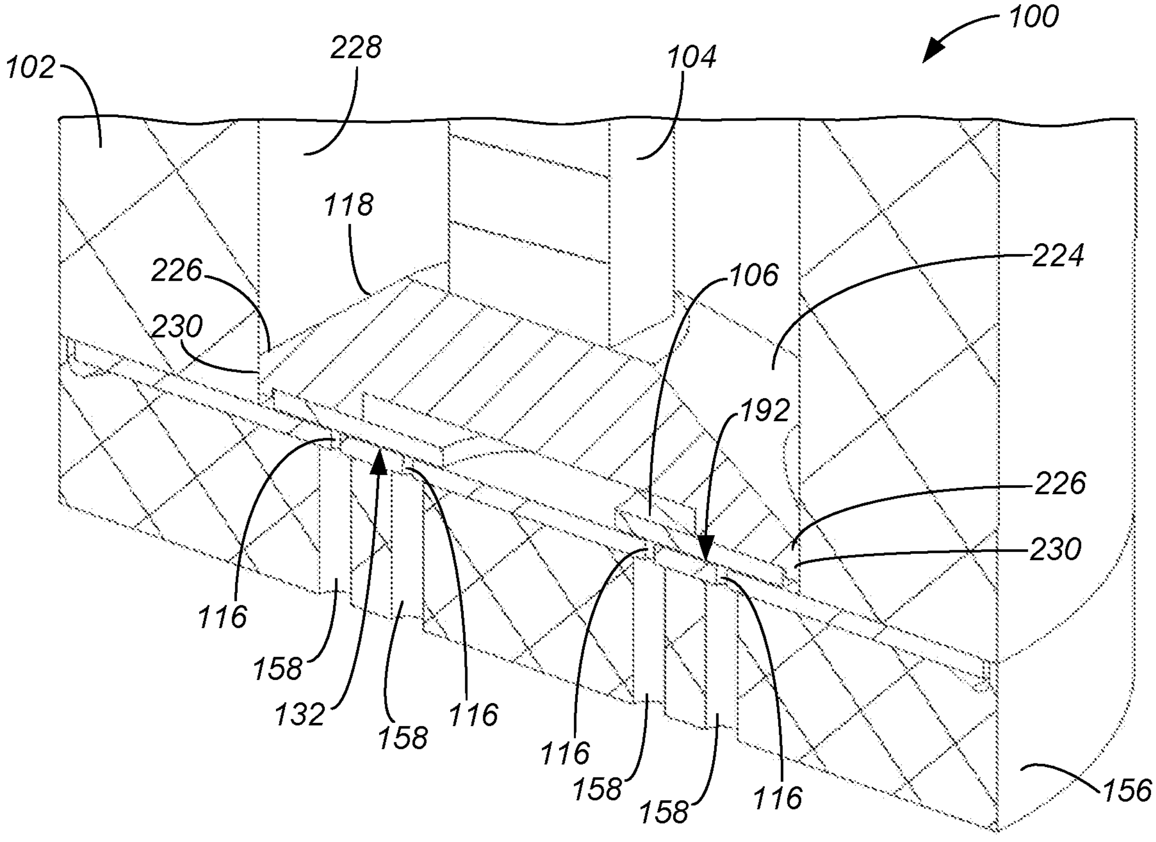
100
102
228
104
118
224
226
106
230
192
226
230
116
158
132
158
116
116
158
158
116
156

FIG. 25

FLUIDIC CONTROL VALVE WITH SMALL DISPLACEMENT ACTUATORS

CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part of and claims priority to U.S. patent application Ser. No. 15/399,150, filed Jan. 5, 2017, which is based on and claims the benefit of U.S. provisional patent application Ser. No. 62/287,655, filed Jan. 27, 2016, the contents of which are hereby incorporated by reference in their entirety.

GOVERNMENT FUNDING

This invention was made with government support under EEC-0540834 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

Embodiments of the present disclosure are directed to a fluidic control valve and, more specifically, to a valve which utilizes actuators having small displacements without the need for displacement amplification mechanisms. Some embodiments include components having both macro-scale and micro-scale features, such as features that are formed using micro-electromechanical systems (MEMS) device fabrication techniques. Fluidic control valves in accordance with other embodiments are also disclosed.

A microvalve is a miniature valve that controls the flow and/or pressure of a fluid passing through it. Inside the microvalve, the fluid flows through channels or orifices that are sized to a micrometer scale. Microvalves developed so far can be classified into two types: active and passive. Active microvalves utilize a powered actuator to control the opening and closure of the micro orifice or channel through which the fluid flows. Passive microvalves, on the other hand, have no actuator to control the fluid flow and are simply check valves operated by the pressure of the flowing fluid and its direction of flow. Passive microvalves are often used as part of micropumps. In contrast, active microvalves are usually free standing fluidic control devices.

The majority of active microvalves are used in pneumatic systems. Many of these valves are used in systems that require precision control of gas flow for biomedical and manufacturing processes. More recently, pneumatic active microvalves are seeing potential application in microspacecraft propulsion systems, where weight, volume and power savings are vital. Another promising application of pneumatic active microvalves is in human assist devices, where power consumption and weight should be minimized. A number of studies have also been conducted on microvalves for liquid applications. Most of these serve as check valves in micropumps or as valves in lab-on-a-chip and chemical analysis systems. However, despite continuous development for the past three decades, microvalves have seen limited commercial success due to difficulties in design such as pressure handling capacity, sealing and packaging.

Pneumatic valves utilizing piezoelectric actuators have recently entered the commercial market. Two variants on piezoelectric actuators are most commonly used: "piezostack" actuators and "piezobender" actuators. Piezostack actuators are composed of a stack of many layers of a piezoelectric material. They rely on the change in thickness of a piezoelectric material when a voltage is applied to produce a deflection. They produce relatively large forces but very small deflections. While variants of piezobender actuators exist, the most common is the "cantilevered piezobender". It consists of a cantilever beam which includes a piezoelectric layer applied to either the top or bottom of a passive layer. When the piezoelectric layer is actuated, the strain induced in the layer causes the beam to deflect as a cantilever beam in pure bending. (An alternative architecture consists of using a piezoelectric layer on both the top and bottom surfaces of the beam. One layer is activated to place it in tension, while the opposite layer is activated so as to place it in compression, causing a larger deflection of the beam.) Piezobenders produce larger deflections but very small forces relative to piezostacks.

Current pneumatic valves exploit the benefits of these piezoelectric actuators. The ViVa actuator produced by Viking AT utilizes a piezostack actuator. This actuator requires the inclusion of a mechanical motion amplifier to increase the very small motion of the piezostack into a motion large enough to be useful with a single orifice.

Another pneumatic valve is the "VEMR" or "VEMC" series by Festo, which utilize cantilevered piezobenders rather than piezo stacks to achieve an actuator motion large enough to work with a single orifice. The use of piezobenders generally prevents the use of the valve as a proportional valve at high differential pressures (e.g., above 4 bar).

SUMMARY

Embodiments of the present disclosure are directed to a fluidic control valve and, more specifically, to a valve which utilizes one or more actuators having small displacements, such as one or more piezostack actuators, without the need for displacement amplification mechanisms. Some embodiments include components having both macro-scale and micro-scale features, such as features that are formed using micro-electromechanical systems (MEMS) device fabrication techniques.

In some embodiments, the fluidic control valve is configured to control a flow of fluid through a conduit and includes a piezostack actuactor, a seal plate having a sealing face, an orifice plate including a plurality of orifices, and a suspension connected to the seal plate. The piezostack actuator is configured to displace the seal plate along a longitudinal axis of the conduit between a closed position, in which the sealing face engages the orifice plate, seals the orifices of the orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the orifice plate to open the valve. The suspension is configured to flex and adjust an orientation of the sealing face relative to the orifice plate during movement of the seal plate from the open position to the closed position.

Some embodiments of the fluidic control valve include a piezostack actuator, a seal plate having a sealing face, a seal plate carrier, an orifice plate and a suspension. The seal plate carrier is positioned between the piezostack actuator and the seal plate, and is configured to drive the seal plate along the longitudinal axis in response to expansion and contraction of the piezostack actuator. The orifice plate includes first and second opposing surfaces, through which at least twenty orifices extend, each orifice having a diameter of about 10 microns to about 500 microns. The suspension includes a peripheral support and a plurality of flexure arms connecting the seal plate to the peripheral support. The piezostack actuator is configured to displace the seal plate carrier and the seal plate along a longitudinal axis of the conduit between a closed position, in which the sealing face engages the first surface of the orifice plate, seals the orifices of the

orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the first surface of the orifice plate to open the valve. The suspension is configured to flex and adjust an orientation of the sealing face relative to the first surface of the orifice plate during movement of the seal plate from the open position to the closed position.

This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter. The claimed subject matter is not limited to implementations that solve any or all disadvantages noted in the Background.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1** and **2** are simplified diagrams of a valve formed in accordance with embodiments of the present disclosure in closed and open states, respectively.

FIGS. **3-5** respectively show an isometric view of a valve within conduit with a portion of the conduit removed, an isometric exploded view of a valve, and an isometric cross-sectional view of a valve within conduit, in accordance with embodiments of the present disclosure.

FIGS. **6**A and **6**B respectively show an isometric view of a seal plate in accordance with embodiments of the present disclosure, and a magnified isometric view of a portion of an orifice plate in accordance with embodiments of the present disclosure.

FIGS. **6**C and **6**D are an isometric view of an exemplary orifice plate, and an isometric cross-sectional view of a seal plate and the orifice plate of FIG. **6**C taken generally along a plane that is perpendicular to a longitudinal axis, in accordance with embodiments of the present disclosure.

FIGS. **7**A and **7**B are isometric cross-sectional and side cross-sectional views of an orifice plate having exemplary contoured orifices, in accordance with embodiments of the present disclosure.

FIG. **8** is an isometric cross-sectional view of an exemplary valve, in accordance with embodiments of the present disclosure.

FIG. **9** is a side cross-sectional view of a valve in accordance with embodiments of the present disclosure.

FIGS. **10-13** illustrate simplified diagrams of a multi-piezostack actuator valve in accordance with embodiments of the present disclosure in various states of operation.

FIG. **14** is an isometric view of an exemplary multi-piezostack actuator valve within a flow conduit in accordance with embodiments of the present disclosure.

FIG. **15** is a simplified view of a portion of an orifice plate in accordance with embodiments of the present disclosure.

FIG. **16** is a simplified side cross-sectional view of a portion of a valve illustrating an exaggerated example of a seal plate failing to seal orifices of an orifice plate when in a closed position.

FIGS. **17**A-C respectively are simplified side cross-sectional views of a portion of an exemplary valve having a suspension with a seal plate in an open position, an intermediary position, and a closed position, in accordance with embodiments of the present disclosure.

FIG. **18** is a simplified isometric view of a valve, in accordance with embodiments of the present disclosure.

FIG. **19** is a simplified cross-sectional view of the valve shown in FIG. **18** taken generally along line **19-19**.

FIGS. **20** and **21** respectively are simplified isometric and top views of a suspension assembly of a valve, in accordance with embodiments of the present disclosure.

FIG. **22** is a simplified isometric cross-sectional view of the suspension assembly taken generally along line **22-22** of FIG. **21**.

FIG. **23** is a simplified side cross-sectional view of a portion of the suspension assembly, in accordance with embodiments of the present disclosure.

FIG. **24** is an isometric view of an exemplary seal plate carrier supporting a seal plate, in accordance with embodiments of the present disclosure.

FIG. **25** is an isometric cross-sectional view of a valve including the seal plate carrier of FIG. **24**, in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

Embodiments of the present disclosure are described more fully hereinafter with reference to the accompanying drawings. Elements that are identified using the same or similar reference characters refer to the same or similar elements. The various embodiments of the invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art.

Specific details are given in the following description to provide a thorough understanding of the embodiments. However, it is understood by those of ordinary skill in the art that the embodiments may be practiced without these specific details. For example, circuits, systems, networks, processes, frames, supports, connectors, motors, processors, and other components may not be shown, or shown in block diagram form in order to not obscure the embodiments in unnecessary detail.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element, or intervening elements may be present. In contrast, if an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. Thus, a first element could be termed a second element without departing from the teachings of the present invention.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

As will further be appreciated by one of skill in the art, embodiments of the present invention may be embodied as methods, systems, devices, and/or computer program products, for example. The computer program or software aspect of the present invention may comprise computer readable instructions or code stored in a computer readable medium or memory. Execution of the program instructions by one or more processors (e.g., central processing unit) results in the one or more processors performing one or more functions or method steps described herein. Any suitable patent subject matter eligible computer readable media or memory may be utilized including, for example, hard disks, CD-ROMs, optical storage devices, or magnetic storage devices. Such computer readable media or memory do not include transitory waves or signals.

The computer-usable or computer-readable medium or memory may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. More specific examples (a non-exhaustive list) of the computer-readable medium would include the following: an electrical connection having one or more wires, a portable computer diskette, a random axis memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), an optical fiber, and a portable compact disc read-only memory (CD-ROM). Note that the computer-usable or computer-readable medium could even be paper or another suitable medium upon which the program is printed, as the program can be electronically captured, via, for instance, optical scanning of the paper or other medium, then compiled, interpreted, or otherwise processed in a suitable manner, if necessary, and then stored in a computer memory.

Embodiments of the invention generally relate to a fluidic control valve or valve. Some embodiments of the valve are configured to provide proportional flow control. Embodiments of the valve may be used for pneumatic or hydraulic applications.

FIGS. **1** and **2** are simplified diagrams of a valve **100** formed in accordance with embodiments of the present disclosure in closed and open states, respectively. In some embodiments, the valve **100** includes or is mounted within a housing or conduit **102** that defines a fluid flow path, such as using a suitable bracket **103**. When the valve **100** is in the closed state (FIG. **1**), fluid flow through the conduit **102** is prevented, and when the valve **100** is in the open state, a flow of fluid is allowed to travel through the conduit **102**, as indicated by the arrows in FIG. **2**.

In some embodiments, the valve **100** comprises a piezostack or piezostack actuator **104**, a seal plate **106**, and an orifice plate **108**. In some embodiments the valve **100** includes a controller **110** and a voltage supply **112**. In some embodiments, the controller **110** represents one or more microprocessors and other circuit elements that are configured to control the voltage source **112** in response to the execution of program instructions, or an input, and facilitate the performance of one or more functions described herein. The program instructions may be stored in memory that is accessible by the one or more processors of the controller **110**, such as local memory of the controller **110** or remote memory that is accessible through a network, for example.

The piezostack **104** is configured to expand and contract along a longitudinal axis **114** in response to the voltage supplied by the voltage source **112**. When in an expanded state (FIG. **1**), an end **115** of the piezostack **104** presses the seal plate **106** against the orifice plate **108**. This seals the plurality of orifices **116** of the orifice plate **108** and places the valve **100** in the closed position, as shown in FIG. **1**. When the piezostack **104** is in a contracted state, the seal plate **106** is displaced from the orifice plate **108** and fluid can flow through the plurality of orifices **116** of the orifice plate **108** and through the conduit **102**, as shown in FIG. **2**. In some embodiments, the piezostack **104** may be placed in states between the contracted and expanded states to allow for proportional control of the flow of fluid through the conduit **102**.

The piezostack **104** requires low actuation power. The piezostack **104** is a capacitive device that requires near zero power to hold it in a specified position, regardless of whether that position is fully closed (FIG. **1**), fully open (FIG. **2**), or anywhere in between. This provides advantages over conventional valves that utilize a magnetic actuator, as such actuators consume power constantly while being held at any position other than their default zero position. Therefore, the valve **100** utilizing the piezostack **104** saves substantial amounts of electric actuation energy compared to conventional magnetically actuated valves. Additionally, the operating temperature of the piezostack **104** does not noticeably increase when held at a constant position.

Exemplary piezostack actuators that may be suitable for uses as the piezostack **104** include those manufactured by Thorlabs Inc. (www.thorlabs.com), such as Item #PK2JUP1, Item #PK2FVP1, Item #PK2FVP2, Item #PK4GA3H5P2, Part #AE0505D16F, and Part #PZS001, or those manufactured by Piezo Systems, Inc. (www.piezo.com), such as Part #TS18-H5-202.

In some embodiments, the orifice plate **108** includes a plurality of orifices **116** that extend through the orifice plate **108**. In some embodiments, the orifices **116** are substantially cylindrical and extend substantially parallel to the longitudinal axis **114** when the orifice plate **108** is oriented perpendicularly to the longitudinal axis **114**, as shown in FIG. **1**. Embodiments of the orifices **116** include orifices having a circular cross-sectional shape, a rectangular cross-sectional shape, or other shape.

FIGS. **3**-**5** respectively show an isometric view of an exemplary valve **100** formed in accordance with embodiments of the present disclosure within the conduit **102** with a portion of the conduit **102** removed, an isometric exploded view of elements of the valve **100**, and an isometric cross-sectional view of the valve **100** within the conduit **102**.

In some embodiments, the valve **100** includes a seal plate carrier **118** that is positioned between the piezostack **104** and the seal plate **106**. Expansion and contraction of the piezostack **104** along the longitudinal axis **114** drives the seal plate carrier **118** and the attached seal plate **106** along the longitudinal axis **114** either toward or away from the orifice plate **108**. In some embodiments, the seal plate **106** includes a central opening **120** and the seal plate carrier **118** includes one or more passages **122**. The passages **122** allow for fluid to flow through the central opening **120** when the valve **100** is in an open position (i.e., not closed), as indicated in FIG. **2**. In some embodiments, a radial gap **124** extends between the seal plate **106** and the conduit **102**, through which fluid can flow when the valve **100** is in an open position, as indicated in FIG. **2**. In some embodiments, the direction of fluid flow is the reverse of that shown in FIG. **2**.

In some embodiments, the piezostack actuator **104** includes a center hole **125** through which fluid may flow to the central opening **120** of the seal plate **106**, as indicated in phantom lines in FIG. **3**. One suitable piezostack **104** that includes a center hole is the Thorlabs PK4GA3H5P2 piezostack.

In some embodiments, the valve **100** does not utilize a mechanical motion amplifier to increase the very small motion of the piezostack **104** along the longitudinal axis **114**. In some embodiments, the displacement of the seal plate **106** along the axis **114** relative to the orifice plate **108** has a 1:1 ratio to the movement of the piezostack **104** along the longitudinal axis **114**. That is, movement of the piezostack **104** is directly translated to movement of the seal plate **106** along the axis **114**. Thus, each micron of movement of the end **115** of the piezostack **104** causes a micron of movement of the seal plate **106**.

In some embodiments, the orifice plate **108** includes an array of micro-scale orifices **116** rather than a single, large orifice, as in conventional valves. The diameter of each of the orifices **116** is sized to be approximately four times the maximum displacement of the end **115** of piezostack **104** along the longitudinal axis **114**. For example, if the piezostack **104** is capable of a 15 micron deflection, then the orifices **116** are sized to have a diameter of approximately 40-60 microns each. The basis of this is that the flow area around the periphery of the orifice **116** times the displacement of the end **115** of piezostack **104** will match the area of the orifice when the end **115** of the piezostack **104** is displaced 25% of the diameter of the orifices **116** from the plate **108**. The number of orifices **116** is selected to produce a summed area equal to the desired area of a single, equivalent orifice. For example, the flow capacity of a single orifice having a diameter of 1.25 mm would be approximately equaled by an array of 630 orifices each having a diameter of 50 microns.

In some embodiments, the orifices **116** have a diameter of about 10 microns to about 500 microns, including more specific ranges of 10 microns to 50 microns, less than 50 microns, less than 100 microns, less than 150 microns, less than 200 microns, less than 250 microns, less than 300 microns, less than 350 microns, less than 400 microns, less than 450 microns, and less than 500 microns. In some embodiments, the orifices **116** are fabricated using a micromachining process.

In some embodiments, the orifice plate **108** includes 20 or more orifices **116**, such as 20-5,000 orifices **116**. In more specific embodiments, the orifice plate **108** includes more than 30 orifices **116**, more than 50 orifices **116**, and more than 100 orifices **116**.

In some embodiments, a circular opening having an area that is equivalent to the total area of the orifices **116** has a diameter that is larger than four times the displacement of the end **115** of piezostack **104** along the longitudinal axis **114** or the distance the piezostack **104** displaces the seal plate **106** from the orifice plate **108**, when in the open position, such as a full open position (e.g., maximum displacement).

In some embodiments, the number of orifices **116** is selected to be equal to or exceed the area of a single, equivalent circular orifice divided by the product of the perimeter of each orifice **116** times the maximum displacement of the piezostack **104**. For example, the flow capacity of a single orifice having a diameter of 1.25 mm would be approximately equaled by an array of 130 orifices **116** each having a diameter of 200 microns if the maximum displacement of piezostack **104** is 15 microns. In some embodiments, the diameter of the orifices **116** in orifice plate **108** may be large enough so that they can be machined using conventional machining processes rather than micro-machining.

In some embodiments, the orifice plate **108** is thin. In some embodiments, the orifice plate **108** has a thickness, through which the orifices **116** extend, that is less than approximately 300 microns, such as about 50 to about 250 microns. Other thicknesses for the orifice plate **108** may also be used, such as greater than 500 microns, and greater than 1 mm, for example. For relatively thick versions of the orifice plate **108** (e.g., thickness of greater than 500 microns), the support plate described below may be unnecessary.

In some embodiments, the valve **100** includes a support plate **128** that supports the orifice plate **108**, as shown in FIGS. **1-5**. The orifice plate **108** and the support plate **128** may be formed of any suitable material, such as stainless steel or aluminum, for example. In some embodiments, the orifice plate **108** and/or the support plate **128** are formed of silicon. This allows the plates **108** and **128** to be micro-machined using processes that are well established for fabricating MEMS devices. Silicon also adapts well to eutectic bonding, which can be used to bond the orifice plate **108** to the support plate **128**. In some embodiments, other bonding methods may be used.

The support plate **128** generally overcomes two challenges. The first challenge stems from the fact that the depth to which an approximately 50 micron hole can be etched is limited. This first challenge is surmounted by reducing the thickness of the orifice plate **108** containing the small orifices **116**. The second challenge is making the orifice plate **108** containing the array of the orifices **116** strong enough to withstand the operating pressure applied across it. As mentioned above, the plates **108** and **128** may each be formed of silicon and can be micro-machined using established MEMS fabrication techniques. However, silicon is a brittle material. In addition, the tiny orifices **116** act as stress concentrators, further lowering the strength of the orifice plate **108**. The second challenge is surmounted by mounting the orifice plate **108** on the thicker support plate **128** containing the orifices **130** having 2-5 times the diameter of the holes **116** in the orifice plate **108**. It then becomes feasible to etch the larger diameter holes **130** through the thicker plate **128**, and the larger holes **130** induce lower levels of stress concentration. Therefore, the combination of the orifice plate **108** with the support plate **128** can be designed to withstand the total intended operating pressure differential.

The support plate **128** may be formed out of any suitable material such as steel, aluminum, or engineering plastic. The support plate **128** operates to prevent deflection of the orifice plate **108** through direct contact with the orifice plate **108** in response to a pressure difference on opposing sides of the orifice plate **108**, which creates a force on the orifice plate **108**. In some cases, without the support plate **128**, deflection of the orifice plate **108** could be substantial in relation to the deflection of the piezostack actuator **104** used to control the movement of the seal plate **106**. In the case that the deflection is substantial, the piezostack actuator **104** may not be able to move the seal plate **106** into contact with portions of the orifice plate **108**, and the valve **100** would be unable to close. Thus, the support plate **128** prevents deflection and fracture of the very thin orifice plate **108**, and allows the valve **100** to fully close even under significant pressure drops across the orifice plate **108**.

In some embodiments, the support plate **128** is positioned on a downstream side of the orifice plate **108** relative to the direction of fluid flow through the conduit **102**, as illustrated in FIGS. **1-5**. Alternatively, the support plate **128** may be located on the upstream side of the orifice plate **108** relative to the direction of flow through the conduit **102**, and the seal plate **106** and piezostack **104** may be located on the downstream side. In this alternative embodiment, the seal plate **106** is configured to seal the orifices **130** of the support plate **128** when the valve **100** is in the closed state.

The thickness of the support plate **128** measured along the longitudinal axis **114** is generally much thicker than the orifice plate **108** to provide the necessary support for the orifice plate **108**. In some embodiments, the support plate **128** has a thickness of more than 500 microns. However, other thicknesses of the support plate **128** may also be used. In some embodiments, the support plate **128** comprises multiple plates that are stacked together to the desired thickness.

In some embodiments, the support plate **128** is stiffened using any suitable conventional technique. In some embodiments, the support plate **128** includes webbing or ribs on the opposing side from the seal plate **106** to increase its stiffness.

In some embodiments, a support plate frame **156** is positioned on a downstream side of the orifice plate **108**, as shown in FIG. **4**. The support plate frame **156** may support or replace the support plate **128**, and operates to reduce the deflection of the orifice plate **108**, and the support plate **128** (if present). The frame **156** may be integrally formed with the orifice plate **108** and/or the support plate **128**. Reducing the deflection of the orifice plate **108** reduces the possibility of leakage through the valve **100** at or near the closed state. Reducing the deflection also lowers the stresses in the orifice plate **108** and the optional support plate **128**. In some embodiments, the support plate frame **156** includes one or more passages **158** that extend through the frame **156** substantially parallel to the longitudinal axis **114**. The passages **158** allow fluid to flow downstream through orifices **116** in the orifice plate **108** and through the orifices **130** in the optional support plate **128**.

In some embodiments, the support plate **128** includes at least one opening or orifice **130** that is aligned with orifices **116** of the orifice plate **108** and allows fluid flowing through the orifices **116** to pass through the support plate **128**. In some embodiments, the support plate **128** includes a plurality of orifices **130**, each of which is aligned with one or more of the orifices **116** of the orifice plate **108**. Thus, in some embodiments, one of the orifices **130** may provide an opening through which fluid traveling through two or more of the orifices **116** may flow. In some embodiments, each of the plurality of the orifices in the support plate **128** corresponds to one of the orifices **116** of the orifice plate **108**. Thus, in some embodiments, the support plate **128** includes an array of orifices **130** that directly correspond to the array of orifices **116**. Accordingly, in some embodiments, the array of the orifices **130** of the support plate **128** has a pattern that matches the pattern of the array of the orifices **116** of the orifice plate **108**. In some embodiments, the arrays of the orifices **116** and the orifices **130** have a circular pattern, as shown in FIG. **4**. Other patterns of the arrays of the orifices **116** and **130** may also be used.

The circular pattern of the orifices **116** is desired to minimize the distance between the edge of the seal plate **106** and the innermost orifice **116**. For example, if the orifices **116** are arranged in a rectangular grid pattern and are sealed with a square seal plate **106**, the minimum distance from the edge of the seal plate **106** to the innermost orifice **116** will be increased significantly. Optionally, pockets can be etched into the sealing face of the seal plate **106** outside the area that covers the orifices **116**, and/or pockets can be etched into the sealing face of the orifice plate **108** outside of the immediate area around orifices **116**, to further increase flow capacity through the orifices **116**.

Due to the larger thickness of the support plate **128**, the orifices **130** generally have a larger diameter than the orifices **116** of the orifice plate **108**. In some embodiments, the orifices **130** each have a substantially larger diameter than the orifices **116**, such as 2 to 5 times the diameter of each of the orifices **116**.

In some embodiments, the orifices **116** are etched from one side of the orifice plate **108**. This generally requires a very thin orifice plate **108**. In some embodiments, the valve **100** includes the support plate **128** to provide the necessary support for the thin orifice plate **108**, such as discussed above and shown in FIGS. **1-5**.

In some embodiments, the orifices **116** which extend through the orifice plate **108** may be fabricated by etching the orifices **116** extending substantially parallel to center axis **114** partially through the orifice plate **108** into the downstream face of the orifice plate **108**, then etching the remaining depth of the orifices **116** substantially parallel to center axis **114** on the upstream face of the orifice plate **108**. This fabrication technique for etching the orifices **116** eliminates stress concentrations attributable to roughness on the far end of orifices **116** if they are etched from a single side of orifice plate **108**. In some embodiments, the above process may be initiated on the upstream face and completed on the downstream face. In some embodiments, the procedure for fabricating the orifices in orifice plate **108** described earlier in this paragraph may be used to fabricate the orifices in the support plate **128**.

In some embodiments, the orifice plate **108** and/or support plate **128** are supported in a fixed position relative to the conduit **102**, while the end **115** of the piezostack **104** may move relative to the conduit **102** along the axis **114**. The plates **108** and **128** may be supported in an assembly that is mounted to the conduit **102**, or supported through another suitable arrangement.

Thus, some embodiments of the valve **100** include machined or otherwise bulk fabricated ("meso-scale") components with micro-machined ("MEMS-scale" or "micro-scale") components. More specifically, the piezostack **104** and the seal plate **106** are fabricated using conventional manufacturing processes, while the orifice plate **108** is fabricated using MEMS micro-machining or fabrication processes. It is noted that the seal plate **106** may also be fabricated using conventional manufacturing or micro-machining processes. As mentioned above, other exemplary embodiments of the valve include macro-scale orifices **116** in the orifice plate **108**, and macro-scale orifices **130** in the support plate **128**.

The use of the arrays of orifices **116** and **130** makes it possible to greatly reduce the distance the seal plate **106** must be displaced along the longitudinal axis **114** from the orifice plate **108** to fully open the valve **100** while still yielding macro-scale flow rates, such as 1-500 slpm for a pressure drop of 6 to 5 bar. This is important because the piezostack **104** produces a very small deflection of the seal plate **106** along the longitudinal axis **114**. Full flow through the valve **100** is achieved if the seal plate **106** is moved away from the orifice plate **108** by approximately 25% of the equivalent diameter of each orifice **116**. Thus, for instance, when the orifice plate **108** includes an array of 630 orifices **116** each having a diameter of 50 microns, the piezostack **104** needs to move the seal plate **106** approximately 15 microns along the longitudinal axis **114** away from the orifice plate **108** to change the valve **100** from the fully closed position (FIG. **1**) to the fully open position (FIG. **2**), which can be achieved using the piezostack **104**. However, if the valve **100** utilized an equivalent single orifice of 1.25 mm in diameter instead of the array of the orifices **116**, an actuator would be required to deflect the sealing component 300 microns to transition the valve from a fully closed state to a fully open state. Thus, the array of orifices **116** in place of single large orifice makes it possible to implement the valve **100** using the piezostack **104**, without the need for motion amplification mechanisms to increase the displacement of the piezostack **104** along the longitudinal axis **114**.

Another advantage to the valve **100** is that it can be operated at very high speeds. This is made possible due to the very small deflection that is required to transition the valve **100** between the fully closed state to the fully open state. In some embodiments, the valve **100** can achieve response times in the microsecond range, such as 100 microseconds.

In some embodiments, the sealing face **132** of seal plate **106** is a substantially flat surface. In some embodiments, the sealing face **132** of the seal plate **106** includes a plurality of sealing bosses **134**, as illustrated in the isometric view of the seal plate **106** provided in FIG. **6**A. In some embodiments, each of the bosses **134** is configured to be aligned with one of the orifices **116** of the orifice plate **108** when the valve **100** is in the closed state (FIG. **1**). In some embodiments, the sealing bosses **134** are larger than their corresponding orifices **116**, such that they overlay their corresponding orifices **116**. For example, in some embodiments, the diameter of each boss **134** is larger than the diameter of each orifice **116**, or at least as large as the diameter of the corresponding orifice **116**. For example, in some embodiments, if each orifice **116** has a diameter of 50 microns, then the bosses might be sized to 80 microns. Other diameters can be used. Pockets between the bosses increase the area for flow between the orifices **116** and the inner and outer edges of seal plate **106**, thereby increasing the flow capacity of the valve, and reducing throttling losses. Other pocket geometries can be used. In some embodiments, the bosses **134** are formed through a micro-machining process. In other embodiments, the sealing face **132** may include an elastomer layer that facilitates sealing the orifices **116** when the valve **100** is in the closed position. Alternatively or additionally, the sealing face **109** (FIG. **1**) of the orifice plate **108** may include an elastomer layer.

In some embodiments, the orifice plate **108** includes sealing bosses **135** that are each aligned with one of the orifices **116**, as shown in FIG. **6**B. In some embodiments, the sealing bosses **135** are positioned on a sealing face **109** of the orifice plate **108**. In some embodiments, the diameter of each sealing boss **135** is larger than the diameter of each orifice **116**. For example, in some embodiments, if each orifice **116** has a diameter of 50 microns, then the bosses might be sized to 150 microns. Pockets between the bosses increase the area for flow between the orifices **116** and the inner and outer edges of seal plate **106**, thereby increasing the flow capacity of the valve and reducing throttling losses. Other pocket geometries can be used. In some embodiments, the bosses **135** are formed through a micro-machining process.

In some embodiments, the bosses **135** have a contoured profile, as illustrated in FIG. **6**C, which is an isometric view of an exemplary orifice plate **108**. FIG. **6**D is an isometric cross-sectional view of the seal plate **106** and the orifice plate taken generally along a plane that is perpendicular to the longitudinal axis **114**. The seal plate **106** is shown in a closed position, in which the sealing face **132** engages the bosses **135**. The exemplary contoured bosses **135** may have a conical exterior surface **137**, which may have a curved profile, such as a convex or concave profile, or a flat profile. The contoured bosses **135** operate to improve fluid flow between the seal plate **106** and the orifice plate **108** when the seal plate **106** is in the open position (FIG. **2**). The bosses **134** of the seal plate **106** may also be formed to have a contoured exterior surface in a similar manner as the bosses **135**.

Thus, some embodiments of the valve **100** include a seal plate **106** having bosses **134** (FIG. **6**A) and/or an orifice plate **108** having bosses **135**. The bosses **134** and **135** may be contoured to have a curved (e.g., concave or convex) exterior surface, such as illustrated by the curved exterior surface **137** of the bosses **135** shown in FIGS. **6**C and **6**D. The contoured surfaces of the orifice plate **108**, the seal plate **106**, or both, such as through a suitable etching process, can decrease the interaction of moving fluid with the surfaces, reduce the effects of shear stress on the working fluid, and reduce fluid flow resistance.

In some embodiments, the orifices **116** may also be contoured to improve fluid flow through the valve **100** when in the open state including reducing turbulence, reducing shear stresses on the fluid, and/or reducing the pressure drop across the orifice plate, for example. FIGS. **7**A-B are isometric cross-sectional and side cross-sectional views of an orifice plate **108** having exemplary contoured orifices **116**, in accordance with embodiments of the present disclosure.

Rather than being defined by substantially flat cylindrical sidewalls that are approximately parallel to the longitudinal axis **114** or another axis that is perpendicular to the orifice plate **108** (FIG. **1**), the sidewalls of the contoured orifices **116** have a profile that includes portions that are curved or angled relative to the longitudinal axis **114**. In some embodiments, the cross-sectional profile of each of the contoured orifices **116** taken in a plane that extends substantially parallel to the longitudinal axis **114** includes a converging nozzle **138** that tapers from the surface **139**, which may be on the input or upstream side of the orifice plate **108** relative to the fluid flow, and/or a diverging nozzle **141** that tapers from the surface **143**, which may be on the output or downstream side relative to the fluid flow, as illustrated in FIGS. **7**A-B. The sidewalls defining the contoured orifices **116** may include a curved conical surface, such as a curved conical surface having a convex profile, as shown in FIGS. **7**A-B, and/or a flat conical surface that are non-parallel to the longitudinal axis **114**. The contoured orifices **116** could be formed using any suitable technique, such as double-sided etching.

In some embodiments, the valve **100** includes a sensor **136** (FIG. **1**) that is configured to detect the displacement between the seal plate **106** and the orifice plate **108**, to allow for precise control of the displacement of the seal plate **106** from the orifice plate **108** using the controller **110**. In some embodiments, the sensor **136** comprises a capacitive sensor. In some embodiments, the capacitive sensor **136** includes, for example, an electrically conductive coating or layer on the sealing face **132** of the seal plate **106**, and one or more electrodes attached to or embedded within the orifice plate **108**. Other suitable forms of the sensor **136** may also be used.

In some embodiments, the piezostack **104** defaults to an elongated state when in an unpowered state (i.e., zero or nominal voltage applied), and contracts when powered (i.e., voltage applied) to decrease the length of piezostack **104** when a voltage is applied to it. In this case, the exemplary embodiments of the valve **100** illustrated in FIGS. **1-5** would assume the closed state when the piezostack **104** is unpowered, and the valve **100** would assume an open state when sufficiently powered.

In some embodiments, the piezostack **104** defaults to a contracted state when in an unpowered state (i.e., zero or nominal voltage applied), and elongates or expands when powered to increase the length of piezostack **104** when powered (i.e., voltage applied). In this case, the exemplary embodiments of the valve **100** illustrated in FIGS. **1-5** would assume an open state when the piezostack **104** is unpowered, and the valve **100** would assume a closed state when sufficiently powered.

FIG. **8** is an isometric cross-sectional view of an exemplary valve **100** that will assume the closed state when the piezostack **104** is unpowered and in a contracted state, and will assume an open state when the piezostack **104** is powered. The piezostack **104** is connected to a mount **160** having a fixed position relative to the orifice plate **108**. The face **115** of the piezostack **104** extends away from the mount **160** when a voltage is applied to it. A strut mount **170** is connected to the face **115** of the piezostack **104**, so it displaces longitudinally away from the orifice plate **108** when a voltage is applied to the piezostack **104**. In some embodiments, a compression spring may be used to press on the strut mount **170** and maintain the piezostack **104** in compression. Struts **175** are connected to the strut mount **170** and pass through holes **165** in the mount **160**. In some embodiments, the holes **165** in the mount **160** are larger than the cross-sectional area of the struts **165** so that fluid may also pass through the holes **165**. In some embodiments, additional holes may be included in the mount **160** to allow additional cross-sectional areas for fluid flow. The struts **175** are connected to the seal plate **106**. In some embodiments, the mount **160**, the strut mount **170**, the struts **175**, and the seal plate **106** are positioned so that the seal plate **106** contacts the sealing face of the orifice plate **108** when no voltage is applied to the piezostack **104**, sealing the plurality of the orifices **116** of the orifice plate **108** and placing the valve **100** in the closed position. Applying maximum voltage to the piezostack **104** fully displaces the seal plate **106** away from the orifice plate **108**, fully opening the valve **100** for fluid flow through the orifices **116** in the orifice plate **108**, which may be supported by the support plate **128**, in accordance with one or more embodiments described above.

In some embodiments, the coefficient of thermal expansion of the material used for struts **175** may be chosen to minimize the effects of temperature changes on valve performance. In other words, if a change in temperature causes the piezostack to elongate by length 6, then a strut material is chosen so that the struts also elongate by length 6, thereby cancelling the effect of the change in length of the piezostack. In some embodiments, the distance between the sealing face **132** of the seal plate **106** and the sealing face **109** of the orifice plate **108** may be adjustable so that the seal plate **106** may be precisely positioned to fully close the orifices **116** in the orifice plate **108** when the piezostack **104** is unpowered.

In some embodiments, the piezostack **104** may be placed in states between the fully contracted and fully expanded states to allow for proportional control of the flow of fluid through the conduit **102** based on the voltage that is applied to the piezostack **104**. Thus, embodiments of the valves described herein may be opened to varying degrees to allow for variable flow rates through the valves. Since the piezostack **104** is a capacitive device, it only consumes power when moving (if power leakage is disregarded). Thus, the piezostack **104** nominally does not consume any power when held at a fixed position based on an applied voltage.

For example, if the piezostack is contracted in the unpowered state, when a threshold voltage is applied to the piezostack **104** of the valve **100** of FIGS. **1** and **2**, the seal plate **106** moves from the open position (FIG. **2**) a certain distance toward the orifice plate **108**, which allows for a certain flow rate of fluid through the valve **100**. An increase in the voltage applied to the piezostack **104** of the valve **100** causes the seal plate **106** to move closer to the orifice plate **108**, and decreases the flow rate of fluid through the valve **100**. Thus, the voltage that is applied to the piezostack **104** may be adjusted to various levels to change the rate of fluid flow through the valve **100** from a zero flow rate to a maximum flow rate.

FIG. **9** is a side cross-sectional view of an exemplary valve **100**, which assumes a closed position when the piezostack **104** is unpowered and is in a contracted state. Thus, the piezostack **104** elongates rather than contracts when a voltage is applied to it. In some embodiments, a compressive force is maintained on the piezostack **104**, such as by a spring that biases the seal plate carrier **180** toward the piezostack **104**, for example. FIG. **9** illustrates the valve **100** in a state where a voltage is applied to the piezostack **104**, so the piezostack **104** is elongated and the valve **100** is in the open state. In this case, the face **115** of the piezostack **104** displaces longitudinally along the axis **114** in response to the elongation of the piezostack **104**, which also displaces a shaft **150** longitudinally along the axis **114**. In some embodiments, a portion of the piezostack **104** is attached to the conduit **102**, such as through an appropriate bracket **103**, as shown in FIG. **9**. The shaft **150** is connected to the seal plate carrier **180**, which is attached to the seal plate **106**. Thus, movement of the shaft **150** along the axis **114** also moves the seal plate **106** along the axis **114** relative to the orifice plate **108** and the support plate **128**, which are fixed relative to the conduit **102**. Expansion of the piezostack **104** displaces the seal plate **106** from the orifice plate **108** to open the valve **100** and allow fluid to flow through the orifices **116** and the conduit **102**, and contraction of the piezostack **104** drives the seal plate **106** against the orifice plate **108** to seal the orifices **116** and close the valve **100**.

In some embodiments, the seal plate carrier **180** may include passages to allow fluid to pass through it and into the center hole **120** of the seal plate **106**. If no voltage is applied to piezostack **104**, the face **115** of the piezostack **104** moves to the right in FIG. **9**, displacing the shaft **150** and the seal plate carrier **180** and the seal plate **106** to the right to the point where the sealing face **132** of the seal plate **106** contacts the surface of the orifice plate **108**, blocking flow through the orifices **116** and closing the valve **100**. In some embodiments, the orifice plate **108** and the support plate **128** each include a hole **185**, through which the shaft **150** passes. A seal **152** between the support plate **128** and the shaft **150** prevents fluid flow through the hole **185**. In other embodiments, the seal **152** may be included between the orifice plate **108** and the shaft **150**.

Additional embodiments are directed to a valve **200** having a plurality of piezostack actuators **104** and seal plates **106**. Such a valve allows for precise control of multiple flow rates through the selective actuation of the piezostack actuators **104**. Exemplary embodiments of the multi-piezostack actuator valve **200** will be described with references to FIGS. **10-14**. FIGS. **10-13** illustrate simplified diagrams of multi-piezostack actuator valve **200** in various states of operation. FIG. **14** is an isometric view of an exemplary multi-piezostack actuator valve **200** within a flow conduit **102**, a portion of which is cut away to expose the valve **200**.

In general, the valve **200** includes a plurality of the piezostack actuators **104** and other components that are generally formed in accordance with one or more embodiments described above regarding the valve **100**. Each of the piezostack actuators **104** controls the movement of a corresponding seal plate **106** along the longitudinal axis **114** between closed and open positions. When the seal plates **106** are in their closed position, they seal an array of orifices **116** of an orifice plate **108**, which may be supported by the support plate **128**, in accordance with one or more embodiments described above with regards to the valve **100**. By selectively transitioning the seal plates **106** from their closed position to their open position using the corresponding piezostack **104**, the valve **200** can increment the flow rate of fluid through the conduit **102**.

In the exemplary valve **200** shown in FIGS. **10-13**, three piezostack actuators **104**A-C are used to drive movement of corresponding seal plates **106**A-C along the longitudinal axis **114** between a closed position (FIG. **10**) and open positions (FIG. **13**). When in the closed position, the seal plate **106**A seals an array of orifices **116**A of the orifice plate **108**, the seal plate **106**B seals an array of orifices **116**B of the orifice plate **108**, and the seal plate **106**C seals an array of orifices **116**C of the orifice plate **108**, as shown in FIG. **10**.

Each of the seal plates **106**A-C may be individually actuated from the closed position (FIG. **10**) to the open position to provide a different flow rate of the fluid through the conduit **102**. In some embodiments, each of the arrays of orifices **116**A-**116**C form an equivalent single orifice of the same diameter. In some embodiments, the arrays of orifices **116**A, **116**B, and **116**C form equivalent single orifices of different diameters. In some embodiments, the equivalent areas of the arrays of orifices **116**A-C increase in a binary sequence. For example, one of the seal plates **106** may cover a single orifice **116** of the orifice plate **108**, another seal plate **106** covers two orifices **116** of the orifice plate **108**, another seal plate **106** covers four orifices **116**, another seal plate **106** covers eight orifices **116**, etc. In other embodiments, one of the seal plates **106** may cover 44 orifices **116**, another seal plate **106** covers 88 (2X44) orifices **116**, another seal plate **106** covers 176 (4X44) orifices **116**, another seal plate **106** covers 352 (8X44) orifices **116**, etc. Proportional flow of fluid through the conduit **102** and the valve **200** can be achieved by fully opening a specified number of the orifices **116** of the orifice plate **108** by selectively actuating the seal plates **106** to their fully open states using the corresponding piezostack actuators **104**.

Thus, in operation, a single seal plate **106**, such as seal plate **106**A, may be actuated using the piezostack **104**A to move the seal plate to its open state to provide a corresponding flow rate of fluid through the conduit **102**, as shown in FIG. **11**. A higher flow rate may be achieved by further actuating seal plate **106**C to its fully open state using the corresponding piezostack **104**C, as shown in FIG. **12**. Yet a further increase in the flow rate of the fluid through the conduit **102** may be achieved by actuating the seal plate **106**B to the open state using the corresponding piezostack **104**B, as shown in FIG. **13**.

The valve **200** may be organized substantially as described above with the valve **100**, as shown in FIG. **14**. In some embodiments, the seal plate carrier **118** includes separately moveable segments, generally referred to as **140**, to allow for the individualized actuation of the corresponding seal plate **106**. For example, the piezostack **104**A is configured to drive movement of segment **140**A, which drives movement of the corresponding seal plate segment **106**A along the axis **114** toward or away from the array of orifices **116**A (FIG. **10**) of the orifice plate **108** to either seal the corresponding array of orifices **116**A or open flow through the array of orifices **116**A. Likewise, a piezostack **104**B drives movement of the segment **140**B, which in turn drives movement of the corresponding seal plate **106**B along the longitudinal axis **114** to either seal the corresponding array of orifices **116**B (FIG. **10**) of the orifice plate **108** or open flow through the array of orifices **116**B of the orifice plate **108**. The piezostack **104**C is configured to drive movement of segment **140**C, which drives movement of the corresponding seal plate **106**C along the axis **114** toward or away from the array of orifices **116**C (FIG. **10**) of the orifice plate **108** to either seal the corresponding array of orifices **116**C or open flow through the array of orifices **116**C. A piezostack **104**D is configured to drive movement of a corresponding segment **140**D, which drives movement of the corresponding seal plate **106**D along the axis **114** toward or away from the corresponding array of orifices **116** of the orifice plate **108** to either seal the corresponding array of orifices **116** or open flow through the corresponding array of orifices **116**.

In some embodiments, each of the piezostacks **104** of the valve **200** contracts when a voltage is applied to it. In these embodiments, each piezostack seals the corresponding orifices **116** when unpowered, and contracts when in a powered state to unseal the corresponding orifices **116**. In some embodiments, each of the piezostacks **104** elongates when a voltage is applied to it. In these embodiments, each piezostack opens the corresponding orifices when in an unpowered state, thereby unsealing the corresponding orifices **116**, and elongates or expands when in a powered state to seal the corresponding orifices **116**. In some embodiments, each piezostack **104** of the valve **200** is supported in a similar manner as described above with reference to FIG. **8**, thereby reversing the opening and closing functions described previously.

FIG. **15** is a simplified view of a portion of an orifice plate **108** in accordance with additional embodiments of the present disclosure, in which the orifices **116** are in the form of one or more annular rings, annular segments, annular arcs or linear slots, generally referred to as slots **142**, that are angularly displaced from each other about the central axis of the orifice plate **108**. In some embodiments, the slots **142** are micro-machined through the orifice plate **108**. In some embodiments, a width of the annular ring or slots **142** is sized at approximately twice the expected displacement of the piezostack **104**. The basis of this sizing is that the flow area around both the inner periphery and the outer periphery of annular ring **142** times the displacement of the end **115** of piezostack **104** will match the area of the annular orifice **142** when the sealing face of seal plate **106** is displaced 50% of the width of the annular ring **142** from the sealing face of orifice plate **108** when the width of annular ring **142** is small compared to its diameter.

In some embodiments, the slots **142** are annular segments or arcs, as shown in FIG. **15**. In some embodiments, each end of the slots **42** includes a stress relief hole **144** to reduce stress concentration. In some embodiments, the slots **142** are separated from each other by structural ribs of the plate **108** that extend between the slots **142**, such as between the stress relief holes **144**, for example. In some embodiments, the slots **142** are uniformly distributed around the central axis of the plate **108**. Thus, in some embodiments, the orifice plate

108 includes the same arrangement of slots **142** as the exemplary slots **142** shown in the full quadrant of the plate **108** shown in FIG. **15**.

Exemplary dimensions are also shown in FIG. **15** for slots **142** having an opening area that is equivalent to a single orifice having a diameter of 1.25 mm, with the piezostack having a displacement of approximately 15 μm. In some embodiments, the slots **142** have a width of approximately 30 μm.

Alternative shapes can be used in place of the annular ring or arc segments shown in FIG. **15**. For example, eight linear slots each having a width of 30 microns could be arranged in an octagonal pattern to approximate a circular annulus.

Additional embodiments of the valve **100** include features that stabilize the transition of the seal plate **106** from the open position (FIG. **2**) to the closed position (FIG. **1**), and reduce the likelihood of a seal failure between the sealing face **132** of the seal plate **106** and the orifice plate **108** when the seal plate **106** is in the closed position.

FIG. **16** is a simplified side cross-sectional view of a portion of the valve **100** illustrating an exaggerated example of the seal plate **106** failing to seal the orifices **116** of the orifice plate **108** when in the closed position due to a non-parallel relationship between the sealing face **132** of the seal plate **106** and the orifice plate **108**. Specifically, the seal plate **106** or the sealing face **132** is at an angle **190** relative to the orifice plate **108** or the surface **192** of the orifice plate, which is approximately perpendicular to the longitudinal axis **114**. As a result, the sealing face **132** of the seal plate **106** engages the orifice plate **108** at one side **194**, while the opposing side **196** is displaced from the orifice plate **108**. The resulting gap between the sealing face **132** and the orifice plate **108** prevents the valve **100** from closing and allows fluid to leak through the orifices **116** of the orifice plate **108**. This misorientation in the orifice plate **108** may occur, for example, due to a shift of the piezostack actuator **104** and/or the seal plate carrier **118** relative to the longitudinal axis **114**, manufacturing errors, or other reasons.

FIGS. **17**A-C respectively are simplified side cross-sectional views of a portion of an exemplary valve **100** that includes a suspension **200** that reduces the likelihood of misorientation between the seal plate **106** and the orifice plate **108** as the seal plate **106** is transitioned from the open position (FIG. **17**A), to an intermediary position (FIG. **17**B), and to the closed position (FIG. **17**C), in accordance with embodiments of the present disclosure. In some embodiments, the suspension **200** is configured to flex and adjust the orientation of the sealing face **132** of the seal plate **106** relative to the orifice plate **108** in response to pressure applied by the seal plate carrier **118** (phantom lines) during movement of the seal plate **106** from the open position to the closed position, including during engagement between the sealing face **132** and the orifice plate **108**. For example, FIG. **17**A illustrates the seal plate **106** in the open position and the sealing face **132** being misoriented with the orifice plate **108** due to the non-parallel relationship between the seal plate **106** or sealing face **132** and the orifice plate **108** or the surface **192** of the orifice plate **108**, as indicated by angle **190**.

As the seal plate **106** is displaced by the piezostack actuator **104** toward the closed position, the side **194** of the sealing face **132** engages the orifice plate **108**, while the opposing side **196** remains displaced from the orifice plate **108** due to the angle **190**, as shown in FIG. **17**B. As the piezostack actuator **104** continues to press the seal plate carrier **118** and the seal plate **106** toward the orifice plate **108**, the suspension **200** flexes and allows the seal plate **106** to pivot and orient the sealing face **132** in the desired parallel relationship with the orifice plate **108** to the fully closed position, which seals the orifices **116**, as shown in FIG. **17**C.

Additionally, the suspension **200** may be configured to apply a continuous compressive force to the piezostack actuator **104**. Thus, when the seal plate **106** is in the open position (FIG. **17**A), the suspension **200** applies a compressive force to the piezostack actuator **104** through the seal plate carrier **118**, for example. This assists in preventing the piezostack actuator **104** from being placed in tension or having a bending moment applied, which can damage the piezostack actuator **104**.

An exemplary suspension **200** formed in accordance with embodiments of the present disclosure that drives parallelism between the sealing face **132** of the seal plate **106** and the surface **192** of the orifice plate **108** will be described with reference to FIGS. **18-23**. FIGS. **18** and **19** respectively are a simplified isometric view of the valve **100**, and a simplified cross-sectional view of the valve **100** shown in FIG. **18** taken generally along line **19-19**. FIGS. **20** and **21** respectively are simplified isometric and top views of a suspension assembly **202** that includes the seal plate **106**, the orifice plate **108** and the suspension **200**, in accordance with embodiments of the present disclosure. FIG. **22** is a simplified isometric cross-sectional view of the suspension assembly **202** taken generally along line **22-22** of FIG. **21**. FIG. **23** is a simplified side cross-sectional view of a portion of the suspension assembly **202**, in accordance with embodiments of the present disclosure.

In some embodiments, the suspension **200** includes a plurality of flexure arms **204**, such as flexure arms **204**A-D, and a peripheral support **206**, as best shown in FIGS. **20** and **21**. Each flexure arm **204** includes a first end **208** that is attached to the seal plate **106**, a second end **210** that is attached to the peripheral support **206**, and an intermediary section **212** connecting the first and second ends **208** and **210**. In some embodiments, the first and second ends **208** and **210** of each flexure arm **204** are angularly displaced from each other by an angle **214** about the longitudinal axis **114**, as shown in FIG. **21**. The angle **214** depends on the number of flexure arms **204**. For example, for four flexure arms **204**, the angle **214** may be approximately 25-80 degrees, for three flexure arms **204**, the angle **214** may be approximately 25-110 degrees. The angles **214** for each of the flexure arms **204** may be the same or different from the other flexure arms **204**.

In some embodiments, the angle **214** between the first and second ends **208** and **210** of the flexure arms **204** is greater than an angle **216** about the longitudinal axis **114** between the first and second ends **208** and **210** of adjoining flexure arms **204**. For example, the angle **214** between the first and second ends **208** and **210** of the flexure arm **204**A is greater than the angle **216** between the first end **208** of the flexure arm **204**A and the second end **210** of the flexure arm **204**D, as shown in FIG. **21**. The angles **216** between the first and second ends **208** and **210** of adjoining flexure arms **204** may be approximately 5-20 degrees.

In some embodiments, the peripheral support **206** extends from the orifice plate **108** along the longitudinal axis **114**, as shown in FIG. **23**. The flexure arms **204** may be supported by the peripheral support **206** such that they are displaced from the orifice plate **108** along the longitudinal axis **114**, as indicated in FIGS. **22** and **23**. This configuration is likely best suited for when the valve **100** is configured to normally be open. As a result, there is a gap **218** between the flexure arms **204** and the orifice plate **108**, as shown in FIG. **23**.

Alternatively, the suspension **200** may be flipped such that the flexure arms **204** and the seal plate **106** lay flat against the orifice plate **108**. This configuration is likely best suited for when the valve **100** is configured to normally be closed. In this configuration, the suspension **200** may be configured to bias the seal plate **106** against the orifice plate **108**.

In some embodiments, the suspension **200** supports the seal plate **106** in the open position when the suspension **200** is in a quiescent state, as shown in FIG. **23**. When in this open state, a gap **220** exists between the sealing face **132** and the surface **192** of the orifice plate **108**, and a fluid flow may pass through the seal plate **106** and the orifices **116** of the orifice plate **108**. In some embodiments, the gap **220** spans a distance of approximately 10-60 micrometers.

The suspension **200** and the suspension assembly **202** may be formed using any suitable technique. In some embodiments, the suspension **200** is integral with the seal plate **106** and is bonded to the surface **192** of the orifice plate **108**. The integral suspension **200** and seal plate **106** may be formed using any suitable technique, such as microfabrication techniques. The peripheral support **206** may be bonded to the surface **192** of the orifice plate **108** using any suitable technique, such as silicon direct bonding, plasma enhanced silicon direct bonding, metallic bonding accomplished via eutectic bonding, or another suitable bonding technique. These bonding methods allow for high levels of control over alignment between the components and assist in ensuring a high level of parallelism between the sealing face **132** of the seal plate **106** and the surface **192** of the orifice plate **108**.

Some embodiments of the seal plate carrier **118** operate to prevent or reduce misalignment between the sealing face **132** of the seal plate **106**. FIGS. **24** and **25** respectively are an isometric view of an exemplary seal plate carrier **118** supporting the seal plate **106**, and an isometric cross-sectional view of the valve **100** illustrating the seal plate carrier **118** of FIG. **24** in operation, in accordance with embodiments of the present disclosure. In general, the seal plate carrier **118** includes a body member **224** and a plurality of tab members **226** that extend radially from the body member **224** relative to the longitudinal axis **114**, and may be evenly angularly distributed about the axis **114** around the body member **224**. The tab members **226** are configured to engage and slide along (slidably engage) the interior wall **228** of the conduit **102** and promote centering of the seal plate carrier **118** and the seal plate **106** within the conduit **102** and in alignment with the longitudinal axis **114**. The tabs **226** each include a side wall **230** that engages the interior wall **228** of the conduit, as shown in FIG. **25**. In some embodiments, the side walls **230** conform to the interior wall **228** of the conduit **102**. The tabs **226** limit the ability of the seal plate carrier **118** to pivot relative to the longitudinal axis **114** during actuation of the valve **100** between the open and closed positions. As a result, the tabs **126** assist in centering the seal plate carrier **118** and the seal plate **106** within the conduit **102** and in the desired alignment with the longitudinal axis **114**.

Although the embodiments of the present disclosure have been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A fluidic control valve configured to control a flow of fluid through a conduit comprising:

a piezostack actuator;

a seal plate including a sealing face;

an orifice plate comprising a plurality of orifices; and

a suspension connected to the seal plate;

wherein:

the piezostack actuator is configured to displace the seal plate along a longitudinal axis of the conduit between a closed position, in which the sealing face engages the orifice plate, seals the orifices of the orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the orifice plate to open the valve; and

the suspension is configured to flex and adjust an orientation of the sealing face relative to the orifice plate during movement of the seal plate from the open position to the closed position.

2. The valve of claim **1**, wherein the suspension includes a plurality of flexure arms and a peripheral support, each flexure arm including a first end attached to the seal plate and a second end attached to the peripheral support.

3. The valve according to claim **2**, further comprising a support plate attached to the orifice plate and configured to stiffen the orifice plate and reduce deflection of the orifice plate in response to engagement with the seal plate, wherein the support plate has a thickness that is greater than 500 microns.

4. The valve according to claim **2**, wherein:

the piezostack actuator is configured to displace the seal plate along the longitudinal axis multiple distances from the orifice plate in response to different voltages applied to the piezostack actuator; and

each of the multiple distances corresponds to a different fluid flow rate through the valve.

5. The valve of claim **2**, wherein the first and second ends of each flexure arm are angularly displaced from each other about the longitudinal axis.

6. The valve of claim **5**, wherein each flexure arm includes an intermediary section connecting the first and second ends and extending between the seal plate and the peripheral support.

7. The valve of claim **6**, wherein the second ends of the flex arms are displaced from the orifice plate along the longitudinal axis.

8. The valve of claim **6**, wherein the first end of a first flexure arm of the plurality of flexure arms is angularly displaced about the longitudinal axis a greater amount from the second end of the first flexure arm than from the second end of a second flexure arm of the plurality of flexure arms.

9. The valve of claim **7**, wherein the peripheral support extends from the orifice plate along the longitudinal axis.

10. The valve according to claim **2**, wherein the first and second ends of each of the flexure arms are angularly displaced from each other about the longitudinal axis from about 25-110 degrees.

11. The valve according to claim **10**, wherein:

the plurality of orifices includes greater than 20 orifices, each orifice having a diameter of about 10 microns to about 500 microns; and

a circle having an area that is equivalent to a total area of the plurality of orifices has a diameter that is greater than four times a maximum distance the piezostack actuator displaces the seal plate from the orifice plate when in the open position.

12. The valve according to claim **10**, wherein each of the plurality of orifices includes a contoured cross-sectional profile taken in a plane that extends parallel to the longitudinal axis that tapers from at least one of the first and second surfaces.

13. The valve according to claim **10**, wherein:

the seal plate includes a plurality of sealing bosses extending from the sealing face toward the orifice plate, each of the sealing bosses is positioned to overlay one of the orifices when the seal plate is in the closed position; or

the orifice plate includes a plurality of sealing bosses extending from a surface of the orifice plate toward the sealing face of the seal plate, each of the sealing bosses surrounding one of the orifices.

14. The valve according to claim **13**, wherein the sealing bosses of the seal plate or the orifice plate include contoured cross-sectional profiles taken in a plane that extends parallel to the longitudinal axis, each defined by a curved exterior surface.

15. A fluidic control valve configured to control a flow of fluid through a conduit comprising:

a piezostack actuator;

a seal plate including a sealing face;

a seal plate carrier between the piezostack actuator and the seal plate and configured to drive the seal plate along the longitudinal axis in response to expansion and contraction of the piezostack actuator;

an orifice plate comprising first and second opposing surfaces, through which at least 20 orifices extend, each orifice having a diameter of about 10 microns to about 500 microns; and

a suspension including a peripheral support and a plurality of flexure arms connecting the seal plate to the peripheral support;

wherein:

the piezostack actuator is configured to displace the seal plate carrier and the seal plate along a longitudinal axis of the conduit between a closed position, in which the sealing face engages the first surface of the orifice plate, seals the orifices of the orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the first surface of the orifice plate to open the valve; and

the suspension is configured to flex and adjust an orientation of the sealing face relative to the first surface of the orifice plate during movement of the seal plate from the open position to the closed position.

16. The valve according to claim **15**, wherein:

the first and second ends of each flexure arm are angularly displaced from each other about the longitudinal axis; and

the second ends of the flex arms are displaced from the orifice plate along the longitudinal axis.

17. The valve according to claim **16**, wherein each flexure arm includes an intermediary section connecting the first and second ends and extending between the seal plate and the peripheral support.

18. The valve according to claim **17**, wherein the first end of a first flexure arm of the plurality of flexure arms is angularly displaced about the longitudinal axis a greater amount from the second end of the first flexure arm than from the second end of a second flexure arm of the plurality of flexure arms.

19. A fluidic control valve configured to control a flow of fluid through a conduit comprising:

a piezostack actuator;

a seal plate including a sealing face;

an orifice plate comprising a plurality of orifices; and

a seal plate carrier between the piezostack actuator and the seal plate and configured to slidably engage the conduit and center the seal plate with a longitudinal axis of the conduit;

wherein the piezostack actuator is configured to displace the seal plate along the longitudinal axis of the conduit between a closed position, in which the sealing face engages the orifice plate, seals the orifices of the orifice plate and closes the valve, and an open position, in which the seal plate is displaced from the orifice plate to open the valve.

20. The valve according to claim **19**, wherein the seal plate carrier includes a body member and plurality of tab members extending radially from the body member relative to the longitudinal axis that slidably engage an interior wall of the conduit.

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